THE INFLUENCE OF LASER RADIATION ON MAGNETIC PROPERTIES OF METALS

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Abstract: *The problem of reducing power losses in electrical plates of Fe-Si, the strict current world is very complex, requiring a thorough knowledge of material structure and linked to it, the configuration of magnetic fields that is structured. This work aims at highlighting the influence laser radiation has on hysteresis losses in Fe-Si sheet plates, and the explanation of differences between the irradiated and non-irradiated sheets. Comparative measurements were carried out between two identical sheets, 300x30x0,5mm, for frequency and induction of magnetic field between 10Hz and 1000Hz, respectively between 100mT and 2100mT. It was noted in both sheets an increase of frequency of active power and apparent power consumption and coercive field intensity and for a fixed frequency was an increase of hysteresis curve area of irradiated sheets. Qualitative and quantitative interpretation of these results was done taking into account the microscopic structure of ferromagnetic materials (sheets of Fe-Si), in the sense that laser radiation increases the degree of fragmentation of Weiss domains, so the number of Bloch walls separating these areas and, also, the number of atoms (magnetic dipoles) inside these walls.*

Keywords: *magnetic properties, hysteresis, laser radiation.*

1. INTRODUCTION

Issue of reducing power losses in electrical sheets is approached by renowned companies and institutions, focusing efforts to obtain methods and technologies to solve them. Remarkable results were obtained in this field of business - Nippon steel Co., which currently produces Fe-Si electrical sheets with grain oriented with the lowest total losses: less than 0.72 W/kg at 1.5 T for thicknesses of 0.3 mm and 0.97 W/kg at 1.7 T and 50 Hz.

The main types of losses and their reduction methods are presented in Table 1.

Table 1. Methods of reducing the total power losses in Fe-Si sheets

Type of loss	Methods for reducing losses
Static loss by hysteresis	
Losses by eddy currents: classical losses	- reduction of sheets thickness - electrical resistance increase by increasing the Si content
Losses by eddy currents: anomalous losses	- grains size control - surface covering with a strained layer - artificial refine of magnetic fields

Of these, the most important are anomalous losses by eddy currents due to the high proportion from the power losses (50%). Anomalous loss reduction can be achieved, especially by subdividing magnetic domains parallel to the rolling direction which is the main structure of Fe-Si alloys. The relation which shows that is [1]:

$$P_{ct} = 1{,}63 \cdot P_{cl} \cdot \frac{2L}{d}, \tag{1}$$

where

$$P_{cl} = \frac{\sigma \pi^2 d^2 B_m^2 \nu^2}{6}, \tag{2}$$

where: P_{ct} - losses by eddy currents; P_{cl} – classical losses by eddy currents; $2L$ – width of the magnetic domain; d – thickness of the magnetic domain; σ - electrical conductivity of the material; υ - magnetizing frequency; B_m – maximum magnetic induction.

It is obvious difficulty in calculating the losses due to limited possibilities for assessing the size of Weiss domains.

In terms of artificial refining of the magnetic fields, the most effective method proved to be the local strain of Fe-Si sheets. This tension can be achieved by scratching, stinging or laser irradiation, the last of the methods being used in related experiments of this paper.

By refining (shredding) increase the number of domains, so the number of Bloch walls separating them. With this increase the number of atoms (magnetic dipoles) inside them. It is known that the internal energy of a ferromagnetic material is composed of: the exchange energy associated to the quantum exchange interaction between the spines of atomic dipoles (WS); the anisotropy energy represented by the energy consumed to magnetize the sample in a different direction of easy magnetization direction (WA); the magnetostriction energy corresponding to the change of sample size in magnetic field (WM); the magnetization energy due to effective magnetization of the sample (Wmag).

In the quantum theory of ferromagnetism, in the absence of an external magnetic field and for equilibrium, it was shown that:

$$W_S \approx \frac{1}{N} \tag{3}$$

and

$$W_A \approx N, \tag{4}$$

where N is the number of atomic dipoles from Bloch walls [1].

Placing the sample in a not very intense magnetic field, such as experience performed, magnetostriction energy becomes negligible. That the amount of the magnetization energy, *Wmag*, which can be determined from the characteristic hysteresis curve, is summarized mainly in terms of the contributions mentioned in equations (3) and (4), is directly influenced by the number N in the walls separators of magnetic domains.

2. THE EXP ERIMENTAL DEVICE USED TO STUDY THE SHEETS MAGNETIZATION

This device consists of a one-sheet Tester (SST) with two vertical yokes using a single sample for measurements. Its shape is rectangular or square, with sizes ranging from 100x15 mm^2 and 500x500 mm^2 [3].

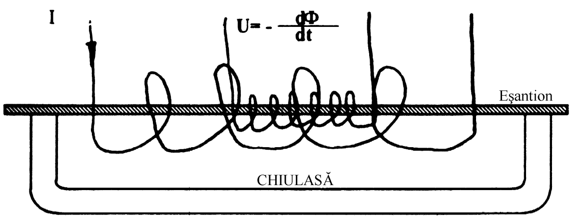

Fig. 1. Structure of the SST's.

Principle structure of a SST is apparent in Fig. 1. The sample is placed inside a medium with two twists – one primary winding, traveled by an alternating current *I(t)* for applying a magnetic field excitation and a secondary winding for measurement of magnetic induction [2].

The strength of excitation magnetic field depends on the number of turns, N_1, and the coil length, *L*, according to the expression [3]:

$$H(t) = \frac{N_1}{l} I(t) \ . \tag{5}$$

Magnetic induction in the jars is determined by measuring the voltage induced in secondary coil of the measuring system, $u_2(t)$:

$$\frac{\mathrm{d}B}{\mathrm{d}t} = -\frac{u_2(t)}{N_2 A_\mathrm{m}} \ , \tag{6}$$

where:

$$B(t) = -\frac{1}{N_2 A_\mathrm{m}} \int_0^t u_2(t)\mathrm{d}t \ , \tag{7}$$

where A_m and N_2 are the transverse area, respectively the number of turns of secondary coil.

3. RESULTS AND DISCUSSIONS

To study the effect of laser irradiation were used 2 identical sheets, size 300x30x0.5mm, which are known: density, $\rho = 7650$ kg/m^3, conductivity, $\sigma = 2{,}2 \cdot 10^3 \Omega^{-1} m^{-1}$, Curie temperature, $T_C = 746^\circ$C. One of them was irradiated using a Nd:YAG laser with following characteristics: wavelength of radiation λ = 1064 nm, pulse energy E_p=2,1J, laser spot diameter on the sample d_S = 1,1 mm, distance between laser spots D = 5 mm. The following are the experimental data results from measurements made (Table 2) and dependency graphs associated with size change after irradiation, except that the shape and characteristics are representative of the entire rest of irradiation (Figs. 2, 3, 4 [4, 5] and 5).

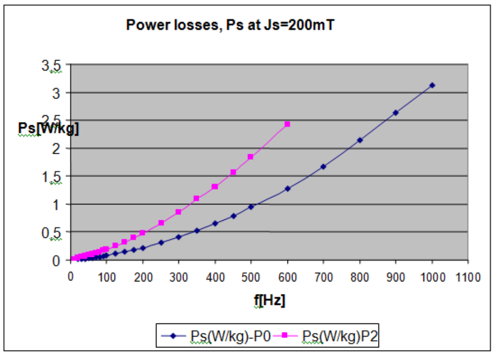

Fig.2. Power losses at J_s=200mT

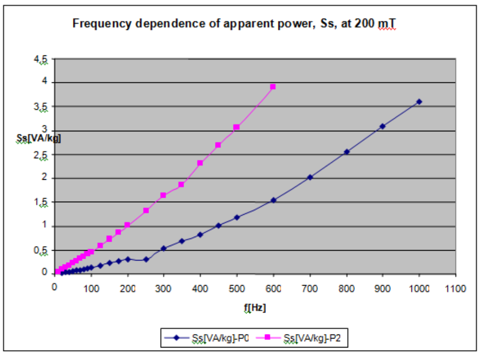

Fig. 3. Frequency dependence of apparent power

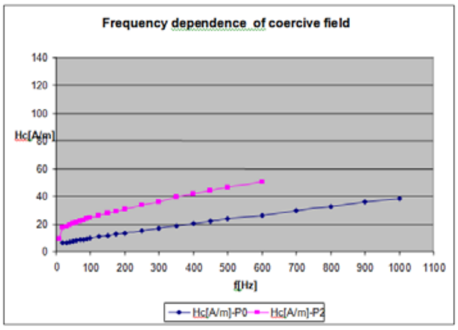

Fig.4. Frequency dependence of coercive field

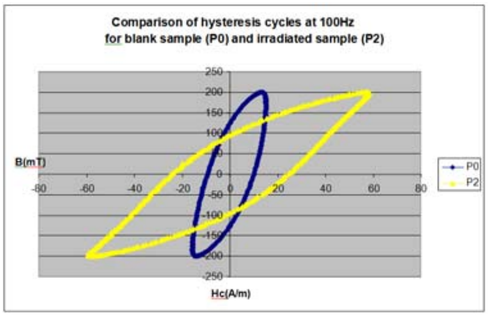

Fig.5. Comparison of hysteresis cycles at 100Hz for blank and irradiated sample

Table 2. Experimental data obtained by irradiation of Fe-Si sheets for 200 mT at different frequencies (P0 – blank, P2 – irradiated sample).

Freq. f(Hz)	Active specific power P(W/kg) P0	Active specific power P(W/kg) P2	Relative magnetic permeability [5] μ_r P0	Relative magnetic permeability [5] μ_r P2	Apparent specific power S[VA/kg] P0	Apparent specific power S[VA/kg] P2	Coerciv field Hc[A/m] P0	Coerciv field Hc[A/m] P2
10	-	0,012093	-	2302,853	-	0,044574	-	9,1291
20	0,009618	0,025615	10696,11	2724,167	0,023396	0,087726	6,266	17,3
30	0,015084	0,040934	11872,58	2762,379	0,032598	0,13109	6,4791	18,287
40	0,021685	0,057704	11662,02	2743,179	0,044493	0,17618	6,987	19,343
50	0,02903	0,075877	11515,33	2754,638	0,056714	0,22287	7,4579	20,206
60	0,03731	0,094953	11212,15	2748,709	0,070334	0,26897	7,9343	21,187
70	0,046093	0,11576	10858,74	2735,703	0,084597	0,31677	8,453	22,025
80	0,05562	0,13767	10525,53	2725,953	0,099662	0,3648	8,8574	22,823
90	0,065558	0,15979	10293,33	2717,385	0,11479	0,41525	9,2337	23,57
100	0,076219	0,18447	10246,09	2706,113	0,12844	0,46474	9,7545	24,454
125	0,10684	0,24762	9278,143	2642,427	0,1768	0,59606	10,83	26,313
150	0,14081	0,31823	8832,148	2638,927	0,22334	0,72635	11,804	27,736
175	0,17721	0,39474	8401,992	2602,166	0,27292	0,86581	12,668	29,212
200	0,21402	0,47686	8510,38	2564,524	0,30835	1,0063	13,483	30,747
250	0,30652	0,65514	7580,562	2493,421	0,30652	1,3078	15,245	33,742
300	0,40652	0,85444	7197,175	2390,394	0,54251	1,6321	16,945	36,161
350	0,52262	1,09474	6576,095	2602,166	0,69298	1,86581	18,459	39,212
400	0,64852	1,309	6303,045	2279,453	0,82665	2,3104	20,143	42,045
450	0,79222	1,5655	5834,199	2197,457	1,0039	2,695	21,818	44,001
500	0,94984	1,8334	5502,293	2153,069	1,178	3,066	23,637	46,379
600	1,2703	2,4272	5070,159	2027,233	1,5356	3,9134	26,207	50,767
700	1,6696	-	4506,216	-	2,0169	-	29,429	-
800	2,1385	-	4039,789	-	2,5582	-	32,815	-
900	2,6262	-	3765,405	-	3,0943	-	35,85	-
1000	3,1277	-	3577,266	-	3,6108	-	38,429	-

4. CONCLUSIONS

As is mentioned in the introduction, laser irradiation is a method of local tensioning (around spots) of metal sheets. It is known that such tension produces segmenting of Weiss domains. This fragmentation allows a significant reduction in eddy currents losses which generate heat, losses associated to magnetic flux variations due to the tendency of atomic magnetic dipoles alignment with external magnetic field (see formula 1).

On the other hand, the same fragmentation produces an increase in hysteresis loss, reflected, first, by the dependency from Figs. 2 and 3 (the curves corresponding to the irradiated sample are above the curves corresponding to the blank sample). About their shape, for each sample separately, the relation between the specific active power PS (active power per unit mass of sample), dissipated in the primary circuit which generates magnetic field, and the magnetic energy stored by sample and represented by the area of hysteresis curve, *Wh*, is given by:

$$P_S = \frac{W_h}{\rho} f \qquad (8)$$

($[W_h] = \frac{J}{m^3}$, $[P_S] = \frac{W}{kg}$), where W_h [6, 7] can be determined quite precisely, the easiest using millimetre paper.

The relation (8) suggests that specific active power PS increase linearly with frequency of magnetic field, and this is well evidenced in figure 2, especially at high frequencies, for the blank and irradiated sample also. With increasing of PS power increase the specific apparent power of the primary circuit, its expression being given by:

$$S = \sqrt{P^2 + P_r^2} = \sqrt{\left(\frac{W_h}{\rho} f\right)^2 + \left(\frac{2\pi LI^2}{\rho V} f\right)^2} = f\sqrt{\left(\frac{W_h}{\rho}\right)^2 + \left(\frac{2\pi LI^2}{\rho V}\right)^2} \ , \qquad (9)$$

where P_r represent specific reactive power and has the expression $P_r = \frac{X_L I^2}{m} = \frac{2\pi f LI^2}{\rho V}$, where *L* and *l* are primary coil inductance, respectively effective intensity of current through the primary circuit; *V* is sample volume.

The dependence *S(f)* is linear, experimental confirmation is also better at higher frequencies (Fig. 3).

Regarding the coercive field HC (Fig. 4), higher values in the irradiated sheet case are due to the fact that irradiation increased the sample magnetization, reflected also by the growth of hysteresis curve surface (Fig. 5), thus cancelling its opposite field must be grater.

Regarding the increasing of power losses by hysteresis due to irradiation (Fig. 5), an explanation would be: by irradiation increases the degree of fragmentation of Weiss domains, so the number of Bloch walls that separate these areas and, with it, the number of atoms (magnetic dipoles) inside them. Increasing the number of dipoles within the walls decreases the number of dipoles within the fields (their sum equals the number of atoms in the sample). For this reason, the energy associated with rotation of the dipoles increases, but decreases the energy needed to align the dipoles brings in domains within the external field. The fact that, overall, increases the energy loss after irradiation, must be understood in the sense that it consumes more energy within the all wall processes than what it wins to all domains orientation.

Quantitatively, as can be observed in relations (3) and (4), increasing the number of dipoles in the walls means a decrease of exchange energy and, simultaneously, an increase of anisotropy energy. Given the foregoing, the contribution limit is lower than that of the exchange anisotropy term.

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