THE INFLUENCE OF LASER RADIATION ON MAGNETIC PROPERTIES OF METALS

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Lucrarea de față are drept obiectiv evidențierea influenței pe care radiația laser o are asupra pierderilor histerezis în tole de Fe-Si, precum şi explicarea diferențelor care apar între tola iradiată şi cea neiradiată. S-au efectuat măsurători comparative între două tole identice, de dimensiuni 300x30x0,5 mm, pentru frecvențe şi pentru inducții ale câmpului magnetizator cuprinse între 10 Hz şi 1000 Hz, respectiv între 100 mT şi 2100 mT. S-a remarcat, în cazul ambelor tole, o creştere cu frecvența a puterii active şi a puterii aparente consumate, precum şi a intensității câmpului coercitiv, iar pentru o frecvență fixată s-a observat o creştere a ariei curbei histerezis în cazul tolei iradiate. Interpretarea calitativă şi cantitativă a acestor rezultate s-a realizat luând în considerare structura microscopică a materialelor feromagnetice (tolele de Fe-Si), în sensul că prin iradiere laser creşte gradul de fragmentare al domeniilor Weiss, deci energia necesară orientării acestora pe direcția câmpului magnetizator [1].

This paper aims at highlighting the influence that the laser radiation has on the hysteresis losses in Fe-Si laminations, and the explanation of differences between irradiated and non-irradiated sheets. Comparative measurements were carried out between two identical sheets, size 300x30x0,5 mm, for frequencies and inductions of magnetic field between 10 Hz and 1000 Hz, respectively between 100 mT and 2100 mT. It was noted with both sheets, an increase of active power and apparent power consumed with frequency, and the coercive field intensity, and for a fixed frequency it can be seen an increase in the hysteresis curve area for irradiated sheet. Qualitative and quantitative interpretation of these results was made considering the microscopic structure of ferromagnetic materials (Fe-Si sheets), meaning that laser irradiation increases the degree of fragmentation of Weiss domains, so the energy needed to guide them on magnetic field direction [1].

Keywords: power losses, Fe-Si electrical sheets, Weiss domains.

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1. Introduction

The problem of reducing power losses in electrical sheets is approached by reputable companies and institutions, focusing special efforts to obtain methods and technologies to solve it [2-6]. Remarkable results in this area have been submitted by the company Nippon-Steel Co., which currently produces Fe-Si electrical sheets with oriented grains 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 reducing methods are presented in Table 1.

Table 1

Reducing methods of the total power losses in Fe-Si sheets

Losses type		Reducing methods of losses
Static losses by hysteresis		- orientation of crystals increasing - inclusions and impurities reducing - internal stresses reducing
Eddy current losses	- classical losses	- sheets thickness reducing - electrical resistance increase by increasing the Si content
	- anomalous losses	- grain size control - surface cover with a strained layer - artificial refining of magnetic fields

Of these, the most important are anomalous losses by eddy currents, due to the high proportion of the total power losses which they have (50%). To reduce them, the most effective method has proven to be a local strain of Fe-Si sheets, a process that can be done by scratching, pinching or laser irradiation. On the other hand, as noted in the table above, internal stress increases the induction of hysteresis losses. Since the losses reduction by eddy current is significantly higher than the hysteresis losses, the local strain is still a widely used technique.

In the performed experiments, the tension was achieved by laser irradiation, and the results were interpreted based on the Weiss model, under which a ferromagnet is composed of microscopic domains separated by Bloch walls.

It is known that the internal energy of a ferromagnetic material is composed of: energy exchange associated to quantum exchange interaction between spins of atomic dipoles (W_S), the energy of anisotropy represented by the energy consumed to magnetize the sample in a different direction with the direction of easy magnetization (W_A), the energy of magnetostriction which corresponds to the changes of sample size in magnetic field (W_M) and the magnetization energy due to the effective magnetization of the sample (W_{mag}) [1]. By refining (grinding) the number of domains and Bloch walls increase. Thereby increasing the degree of anisotropy and quantum exchange interaction weakens favour dipoles alignment in the direction of external magnetic field with additional coupling between them. In this connection, in the quantum theory of ferromagnetism, in the absence of an external magnetic field and for a steady state, it was showed that $W_S \approx \frac{1}{N}$ and $W_A \approx N$, where N represents the number of atomic dipoles in the Bloch walls [7]. Placing the sample in a not very intense magnetic field, $(10^2 - 10^3)mT$, as made experiences, the energy of magnetostriction can be considered negligible.

All these factors suggest the need for higher energy consumed in the process of magnetization of the sample, which was confirmed by experiments carried out. For example, for a frequency of 20 Hz the energy increased from 17 µJ to 43 µJ, and for a frequency of 500 Hz the energy increased from 65 µJ to 126 µJ.

2. Experimental details

The experimental device used in the study of sheets magnetization is represented by a one-sheet tester (SST) with two vertical yokes for measurements using a single sample. Its shape is rectangular or square, with dimensions ranging from 500x500 mm^2 and 100x15 mm^2 [8].

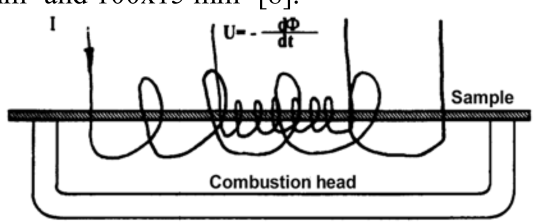


Fig. 1 The structure of SST [9]

The structure of an SST can be observed in Fig. 1. The sample is placed inside of a holder with two coils - a primary winding, crossed by an alternating current $I(t)$ for applying a magnetic field excitation and a secondary winding for measurement of magnetic induction. Closing of the magnetic circuit is achieved via a system composed of two vertical cylinder heads.

The strength of the excitation magnetic field depends on the number of turns, N_1, and the primary coil length, l, according to the expression [10]:

$$H(t) = \frac{N_1}{l} I(t) \qquad (1)$$

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

$$\frac{\mathrm{d}B}{\mathrm{d}t} = -\frac{u_2(t)}{N_2 A_\mathrm{m}} \ , \tag{2}$$

where

$$B(t) = -\frac{1}{N_2 A_\mathrm{m}} \int_0^t u_2(t)\mathrm{d}t \tag{3}$$

where A_m and N_2 represent the cross area, respectively the number of turns of secondary coil.

To study the effect of laser irradiation were used two identical sheets, size *300x30x0,5 mm*, which are known: density $\rho = 7650\ kg/m^3$; conductivity, $\sigma = 2{,}2 \cdot 10^3\,\Omega^{-1}m^{-1}$; Curie temperature, $T_C = 746^oC$. One of them was irradiated using a laser Nd:YAG with the following characteristics: wavelength of radiation, $\lambda = 1064\ nm$; pulse energy, $E_p = 1{,}3\ J$; laser spot diameter on the sample, $d_S = 1\ mm$; distance between laser spots, $D = 5\ mm$.

3. Results

The following are the experimental data derived from measurements taken (Table 2) and corresponding dependency graphs (Figs. 2 and 3), noting that the shape and characteristics are representative of the entire set of irradiation.

Table 2

Experimental data obtained by irradiation of Fe-Si sheets up to 200 mT at different frequencies (P0 – non-irradiated sample; P2 – laser irradiated sample).

Freq. f(Hz)	Specific active power P(W/kg) P0	Specific active power P(W/kg) P2	Apparent specific power S[VA/kg] P0	Apparent specific power S[VA/kg] P2
10	-	0,012093	-	0,044574
20	0,009618	0,025615	0,023396	0,087726
30	0,015084	0,040934	0,032598	0,13109
40	0,021685	0,057704	0,044493	0,17618
50	0,02903	0,075877	0,056714	0,22287
60	0,03731	0,094953	0,070334	0,26897
70	0,046093	0,11576	0,084597	0,31677
80	0,05562	0,13767	0,099662	0,3648
90	0,065558	0,15979	0,11479	0,41525
100	0,076219	0,18447	0,12844	0,46474
125	0,10684	0,24762	0,1768	0,59606
150	0,14081	0,31823	0,22334	0,72635
175	0,17721	0,39474	0,27292	0,86581
200	0,21402	0,47686	0,30835	1,0063

250	0,30652	0,65514	0,30652	1,3078
300	0,40652	0,85444	0,54251	1,6321
350	0,52262	1,09474	0,69298	1,86581
400	0,64852	1,309	0,82665	2,3104
450	0,79222	1,5655	1,0039	2,695
500	0,94984	1,8334	1,178	3,066
600	1,2703	2,4272	1,5356	3,9134
700	1,6696	-	2,0169	-
800	2,1385	-	2,5582	-
900	2,6262	-	3,0943	-
1000	3,1277	-	3,6108	-

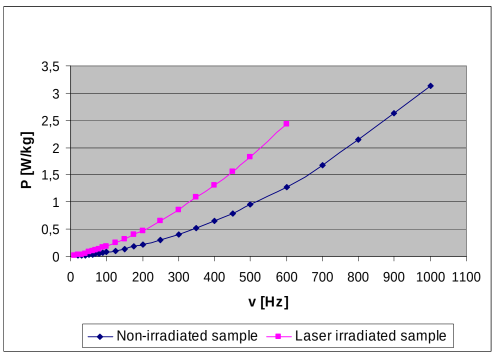


Fig.2 Power losses vs. frequency at 200 mT

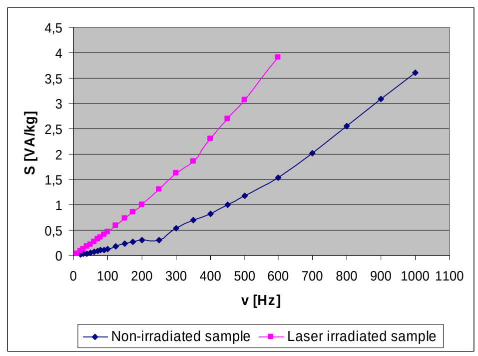


Fig. 3 Apparent power vs. frequency at 200 mT

In the tables 3 and 4 and the figure 4 are mentioned representative examples of hysteresis cycles for the non-irradiated and laser irradiated sample at different values of maximum magnetic induction and magnetic field frequency.

Table 3

Values of maximum magnetic induction and magnetic field frequency in the conditions of B_m = 100 mT and υ =100 Hz.

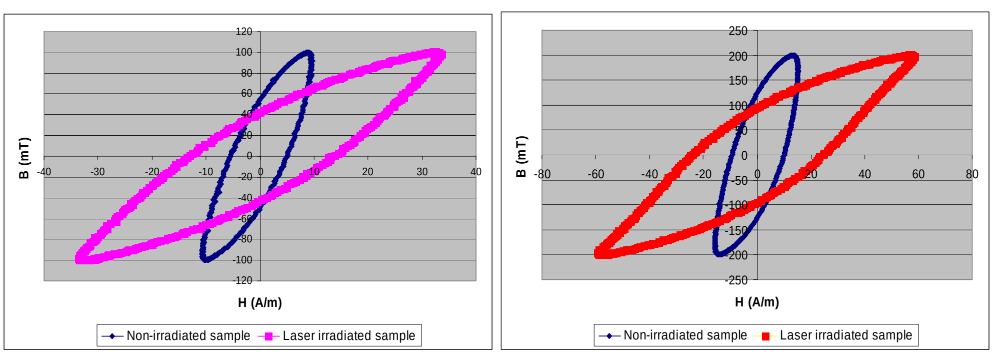
B (mT)		H (A/m)	
Non-irradiated sample	Laser irradiated sample	Non-irradiated sample	Laser irradiated sample
99,63	100,34	8,7421	32,486
93,137	94,91	6,4478	26,848
72,894	75,817	2,3534	14,995
56,075	59,469	0,2382	6,763
36,43	40,233	-2,3121	-0,7808
7,5037	11,552	-4,7836	-10,273
-22,091	-18,348	-7,1852	-17,816
-62,131	-59,415	-9,6138	-26,739
-89,893	-88,693	-10,601	-32,147

-99,76	-100,07	-10,119	-33,498
-90,098	-91,721	-6,9148	-24,926
-62,756	-65,78	-1,9235	-10,122
-37,17	-40,824	1,3433	0,6017
-8,2478	-12,275	4,4078	10,463
61,678	58,75	8,7081	26,697
95,187	94,17	9,5857	32,887
99,926	99,803	8,8908	32,597

Table 4

Values of maximum magnetic induction and magnetic field frequency in the conditions of B_m = 200 mT and υ =100 Hz.

B (mT)		H (A/m)	
Non-irradiated sample	Laser irradiated sample	Non-irradiated sample	Laser irradiated sample
199,76	200,39	13,444	57,321
192,03	192,81	10,207	49,619
167,41	168,75	5,5039	32,081
128,01	130,07	0,4477	13,089
123,36	125,51	-0,0053	11,928
77,273	79,912	-4,2929	-4,7567
19,62	22,417	-8,3028	-19,564
-39,809	-37,414	-11,555	-30,174
-95,75	-94,16	-13,779	-40,217
-143,26	-142,48	-15,178	-49,43
-178	-177,83	-15,644	-55,863
-182,29	-183,13	-8,31	-42,273
-129,09	-131,15	-0,1486	-13,941
-78,642	-81,287	4,6784	4,4776
119,6	118,42	14,359	44,662
189,1	188,96	14,835	56,977
200	199,89	13,513	57,442



a) b)

Fig. 4 Comparison between hysteresis cycles: a) at 100 mT, υ =100 Hz for non-irradiated and laser irradiated sample; b) at 200 mT, υ =100 Hz for non-irradiated and laser irradiated sample

4. Discussions

As mentioned in the introduction, laser irradiation is a method of local tension (around the spots) of metal sheets. It is known that such a tension produces the fragmentation of Weiss domains [1]. This fragmentation allows a significant reduction of losses by eddy currents which generate heat, losses associated to the magnetic flux variations due to the tendency to align the atomic magnetic dipoles with the external magnetic field [11,12].

On the other hand, the same fragmentation causes an increase of power losses in the sample (the sheet), which is showed, firstly, by the dependencies in Figures 2 and 3 (corresponding curves of laser irradiated sample are above the corresponding curves of non-irradiated sample). Related with their shape, for each sample separately, the relationship between specific active power *P* (active power per unit mass of sample) dissipated in the primary circuit which generates magnetic field and magnetic energy stored by the sample and represented by the hysteresis curve area, W_h, is given by:

$$P = C\frac{W_h}{\rho}\upsilon\,, \tag{4}$$

W_h being able to determine fairly accurately, the easiest using millimeter paper or more precisely by numerical integration ($[W_h] = \frac{J}{m^3}$, $[P] = \frac{W}{kg}$). *C* is a dimensionless constant factor of proportionality which depends on the nature of the sample material and is related to the fact that only a fraction of the energy consumed outside is found as a magnetic energy.

Relation (4) suggests that when the frequency of magnetic field increases, the specific active power *P* increases also. This fact is well evidenced only at high frequencies for both laser irradiated and non-irradiated sample (Figure 2).

Once that the power *P* grows, the apparent specific power *S* in the primary circuit increases as well, its expression being given by:

$$S = \sqrt{P^2 + P_r^2} = \sqrt{\left(C\frac{W_h}{\rho}\upsilon\right)^2 + \left(\frac{2\pi\upsilon LI^2}{\rho V}\right)^2} = \upsilon\sqrt{\left(C\frac{W_h}{\rho}\right)^2 + \left(\frac{2\pi LI^2}{\rho V}\right)^2}\,, \tag{5}$$

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

The apparent specific power (*S*) dependence on frequency is linear. This experimental result is confirmed better only at higher frequency, over 200 Hz for laser-irradiated sample and over 500 Hz for non-irradiated sample (Figure 3).

Regarding the increase of power losses by hysteresis due to irradiation (Figs. 4a and 4b), the explanation must be related to those mentioned in the introduction, namely the increasing fragmentation in Weiss areas and the number of Bloch walls separating these domains. Thus, the division is a drop in energy exchange and, simultaneously, an increase of anisotropy energy. Also, the magnetic energy stored in sample and represented by the hysteresis cycle area has increased by irradiation. Neglecting magnetostriction, all three components of the internal energy of the sample were modified by laser irradiation in the sense of the heaviness of magnetization process, so the energy (and power for a single frequency) needed external (consumed) should be higher. This fact is in a good concordance with graphical representations 2 and 3, which show higher values for active and apparent power consumed in the laser-irradiated sample case.

5. Conclusions

The experiments and results require the following conclusions:

In a ferromagnetic sample, the laser irradiation determine the division and the increase of the number of Weiss domains and Bloch walls separating them.

As can be seen in Figs. 4a and 4b, the increase of the magnetic fields involves increasing the magnetic energy stored by the sample, as evidenced by hysteresis cycles plotted.

Also, increasing the number of areas generate lower coupling between atomic dipoles and hence, lower quantum energy exchange. For the same reason there is an increase of anisotropy energy associated to atomic dipole orientation relative to the direction of easy magnetization.

Neglecting magnetostriction, all terms which compose the internal energy of the ferromagnetic sample were influenced in the sense that power consumption of the sample increased (see Figs. 2 and 3).

We should mention that although laser irradiation has a negative influence on hysteresis losses, increasing them, the method is used because it enables a significant reduction of the main sources of power loss, the eddy currents.

Considering the significant economic impact studies on power losses in ferromagnetic materials, we continue research the first step being related to the interpretation of the variations of coercive field intensity, remanent magnetization and magnetic relative permeability by laser irradiation. The results will be published in a future paper.

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