The influence of near IR laser annealing on the magnetic properties of Fe-Si sheet

M. VOICU*, C. OROS, S. DINU
"Valahia" University of Targoviste, Faculty of Sciences and Arts, Science Department, 18 Uniri Blvd., 130024, Targoviste, Romania

A pulsed Nd:YAG laser (*1.064 μm, 3 ms, 1.2 J*) was used to modified the magnetic properties of Fe-Si (*6.5 wt%* Si) sheet targets by laser annealing. The measurements of hysteresis properties were performed with a mini-single strip tester. The experimental results which include the decreasing of relative magnetic permeability and magnetic remanence and the increasing of coercive force after laser irradiation of the target are reported. A discussion about the obtained experimental results in the term of Weiss magnetic domain is given.

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1. Introduction

Fe-Si sheet is a very suitable material and in common use in the form of thin insulated laminations for the electrical devices such as transformers and motor cores. It is known that the addition of silicon in iron lowers the losses associated to eddy current and core loss and the reduction of these losses subsequently leads to the enhancement of the magnetic properties which could allow worldwide large-scale energy savings.

The structure-sensitive properties of magnetic alloys: relative magnetic permeability, coercive force, magnetic remanence and the shape of the hysteresis loop depend not only upon such variables as the degree of internal strain, lattice imperfection and grain size, but also, upon alloying concentration. In general, these properties are associated with the statistical behaviour of an assembly of magnetic domains during the magnetization process and the approach to saturation. Structure-insensitive properties, intrinsic magnetization and the Curie temperature, on the other hand, are properties of individual domains and depend primarily upon the composition of the alloy.

In a first approach the structure-sensitive properties of the ferromagnetic materials can be explained using the Weiss theory (1907). He proposed that all ferromagnetic materials consisted of un-oriented, magnetically saturated regions called domains. In the demagnetized state, the distribution of the directions of magnetization of the domains is random and, therefore, results in an average induction of zero. If a magnetic field is applied, the domains whose directions of magnetization are closest to the direction of applied field grow in size at the expence of the unfavourably oriented domains. In the initial stages, this process proceeds by reversible domain movement. The process continues, however, by irreversible wall movement. In the final step of the approach to magnetic saturation the directions of magnetization of the domains are rotated into the field direction. The coercive force, remanence and magnetic permeability all involve irreversible domain wall movement (sometimes, domain's magnetization rotation) and have a strong dependence on the number and dimension of the magnetic domains of the material.

The crystallographic texture and Weiss magnetic domain size have a strong influence on the magnetic properties of Fe-Si alloys. These microstructural parameters can be modified by laser thermo-mechanical processing of the material without phase transformation [1-6].

We have studied the dependence of the hysteresis properties (relative magnetic permeability, magnetic remanence and coercive force) of Fe-Si sheets irradiated by a pulsed Nd:YAG laser on the magnetic field parameters (maximum magnetic induction in the sample and applied magnetic field frequency).

2. Experimental

We have used a pair of identical Fe-Si targets (*6.5 wt%* Si), $300\times30\times0.5$ mm^3, in the form of thin insulated laminations for the magnetic cores of electrical power transformers. The samples have been irradiated by a pulsed Nd:YAG laser, *1.06* μm wavelength (λ), *3* ms pulse duration at FWHM (τ_p), *1.2 J* average laser energy per pulse (E_p). The temporal and spatial shapes of the laser pulse were Gaussian, both. The laser spot diameter on the sample was *1.1* mm (D) in negative defocusing and the distance between two consecutive laser spot on the sample was *5* mm. The laser irradiations on target were performed in air at normal atmospheric condition. The magnetic properties measurements were performed in a specially designed mini-single strip tester (SST). One of the Fe-Si sheets was laser irradiated and then the magnetic properties were measured. The second sample was not irradiated and the magnetic measurements were performed on it in order to compare the obtained results with the first Fe-Si sheet.

3. Results and discussion

The dependence of the relative magnetic permeability on magnetic field parameters is given in Figs. 1 and 2. Fig. 1 shows the relative magnetic permeability versus the maximum magnetic induction in the sample at *100 Hz* magnetic field frequency and Fig. 2 shows the relative magnetic permeability versus magnetic field frequency at *0.2 T* maximum magnetic induction in the sample.

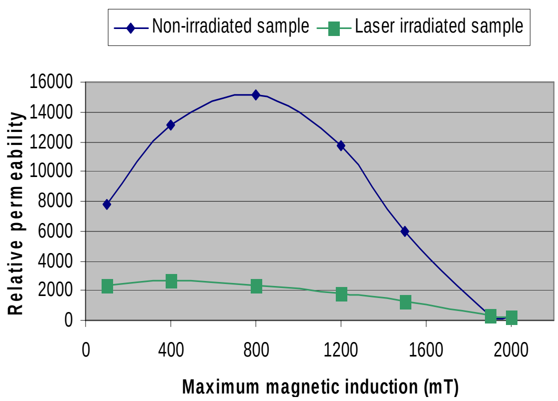

Fig. 1. Relative permeability vs. maximum magnetic induction.

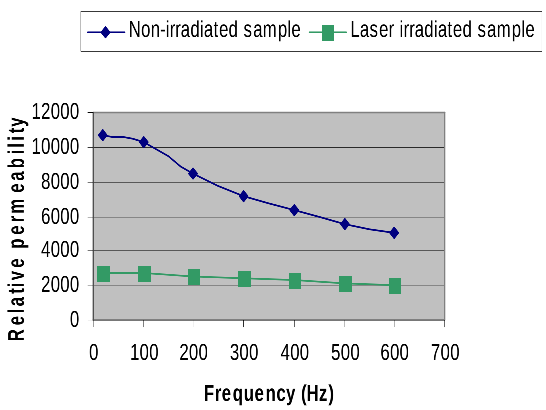

Fig. 2. Relative permeability vs. magnetic field frequency.

From these two graphs results that the relative magnetic permeability decreases after laser irradiation of the target. Also, the relative magnetic permeability decreases for both sheets, laser irradiated and non-irradiated, when the maximum magnetic induction in the sample and applied magnetic field frequency increase, respectively. The decrease of the relative magnetic permeability is significant in the case of non-irradiated sample when magnetic induction and magnetic field frequency vary, respectively, and has not an important variation in the case of the laser irradiated sample.

The dependence of the coercive force on same magnetic field parameters is presented in Figs. 3 and 4. In Fig. 3 the coercive force versus maximum magnetic induction in the sample at *100 Hz* magnetic field frequency is given. The Fig. 4 shows the dependence of the coercive force on the magnetic field frequency at *0.2 T* maximum magnetic induction in the sample.

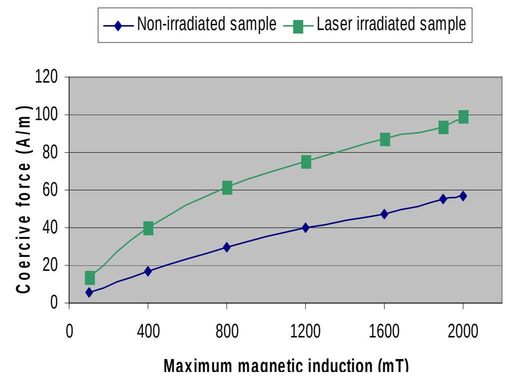

Fig. 3. Coercive force vs. maximum magnetic induction.

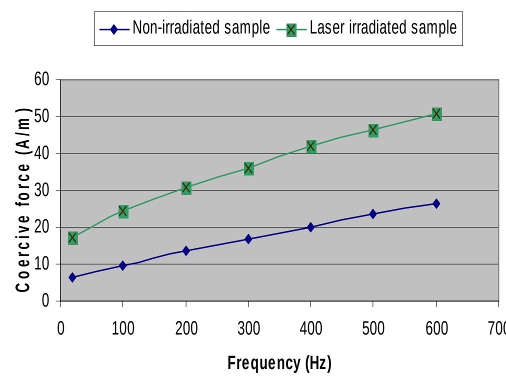

Fig. 4. Coercive force vs. magnetic field frequency.

One can see that the values of the coercive force in all cases presented in Figs. 3 and 4 are bigger after laser irradiation of the target. The coercive force increases in a nearly linear shape in respect to the increasing of the maximum magnetic induction in the samples and to the increasing of the magnetic field frequency, respectively.

The experimental results of the magnetic remanence versus magnetic field parameters (maximum magnetic induction in the sample and magnetic field frequency) are given in Figs. 5 and 6. The values of the magnetic remanence increase for both samples with the maximum magnetic induction and the magnetic field frequency, respectively. The magnetic remanence of the laser irradiated sample is smaller than the magnetic remanence of the non-irradiated sample in all cases presented in Figs. 5 and 6.

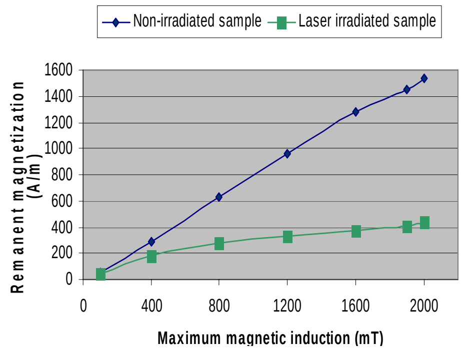

Fig. 5. Remanent magnetization vs. maximum magnetic induction.

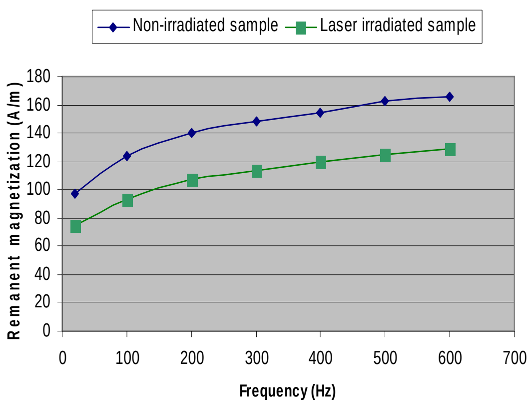

Fig. 6. Remanent magnetization vs. magnetic field frequency.

The hysteresis properties of ferromagnetic materials arise from their Weiss magnetic domain structure and the influence of the magnetization processes that take place in a specimen when the applied magnetic field is changing.

The laser irradiation of ferromagnetic targets is a method to increase by "fragmentation" the number of Weiss magnetic domains. In our experimental conditions, due to the laser parameters: pulse duration and laser pulse energy, this fragmentation is the result of the laser annealing. In order to confirm this laser effect on the target the temperature reached by the target surface at the end of laser pulse can be estimated using the following relation [7]:

$$T(0,\tau_p) = \frac{2AI_0}{k_T}\sqrt{\chi_T \tau_p}\ , \qquad (1)$$

where A is the Nd:YAG laser absorptivity on the Fe-Si target, $I_0 = \dfrac{4E_p}{\pi D^2 \tau_p}$ is the average laser pulse intensity, k_T is the thermal conductivity, χ_T is the diffusivity and τ_p is the laser pulse duration. We have found out from calculations, using relation (1), the theoretical temperature on the sample surface at the end of laser pulse, $T_{theor} \approx 1440\ K$, which is close to the Fe-Si melting temperature $T_{melt} \approx 1588\ K$, in accord with our previous assumption regarding the laser annealing.

When the number of Weiss domains is bigger in a sample the degree of magnetic disorder is bigger also, i.e. the number of magnetic dipole with the same magnetic orientation is smaller. For this reason, the magnetization of the sample with a larger number of Weiss domains is smaller; like in the case of our laser irradiated target.

The magnetic relative permeability is the ratio between magnetic induction in the sample and the external applied magnetic field intensity. From the experimental hysteresis loops, Figs. 7 and 8, one can see that in order to obtain the same maximum magnetic induction in the samples, the applied magnetic field intensity is bigger in the case of laser irradiated sample which have a bigger number of Weiss magnetic domain. For example, from fig. 7 results that in order to obtain the *0.4 T* maximum value of the magnetic induction in the samples the applied magnetic field intensity is $19.73\ A\cdot m^{-1}$ in the case of non-irradiated sample and $116.25\ A\cdot m^{-1}$ in the case of laser irradiated sample. Consequently, the values of the magnetic relative permeability are smaller in the case of the laser irradiated sample than in the case of non-irradiated sample.

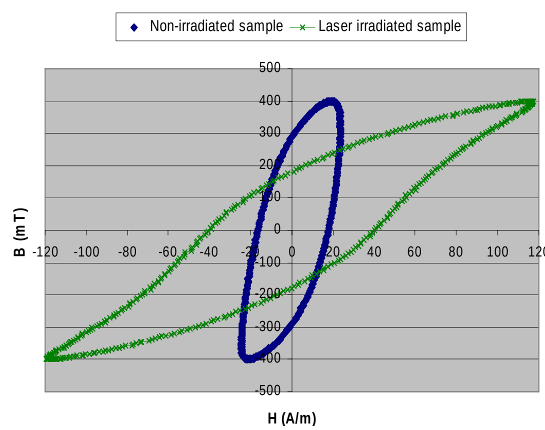

Fig. 7. Hysteresis loop (Bmax = 0.4 T, ν = 100 Hz).

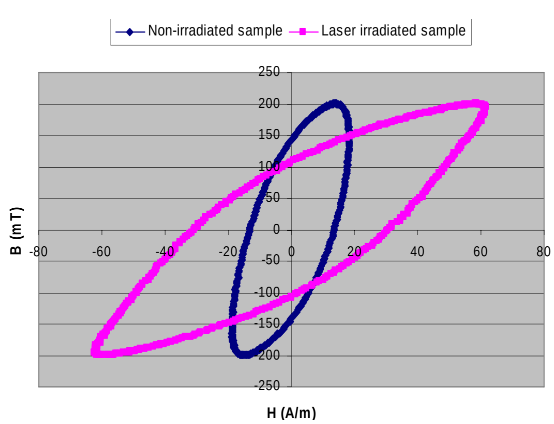

Fig. 8. Hysteresis loop (Bmax = 0.2 T, ν = 200 Hz).

The number and dimension of magnetic domains are important factors regarding the coercive force value. In the case of a sample with a bigger number of magnetic domains the destroy of magnetic order orientation involves an applied magnetic field stronger than in the case of a sample with a smaller number of magnetic domains. When the magnetic domains are bigger in volume there is a bigger movement of inter-domains walls, i.e. a smaller resistance of walls movement and this leads to the decrease of the coercive force, in accord with our experimental results. Kisielewski et al. have obtained a same behavior of coercive force but they have used for irradiation a pulsed fs laser [8].

The magnetic remanence is determined by the final domain magnetization distribution obtained when the material is placed first in a saturating field and then removed to zero field. Each domain magnetization direction will return to an easy direction of magnetization closest to that of the applied field direction. This easy direction is related to the crystal structure and to the magnetic anisotropy energy. The magnetic remanence can consequently be modified by grain orientation or by annealing treatments which change magnetic anisotropy.

The values of magnetic remanence of laser irradiated sample vs. non-irradiated sample involve the number of Weiss magnetic domains. Because this number is bigger in the case of laser irradiated sample, than in the case of non-irradiated sample the magnetic remanence has a smaller value for laser irradiated sample.

The dependence of the magnetic properties on magnetic applied field frequency can be explained in the term of the time of magnetic dipoles re-orientation. When the value of field frequency increases the time of the magnetic dipoles re-orientation decreases and the degree of magnetic disorder remains large.

3. Conclusions

By using a pulsed Nd:YAG laser (*1.064 μm, 3 ms, 1.2 J*) it was possible to produce local transient temperatures modifying the magnetic behavior of Fe-Si samples without significantly affecting their macroscopic layer structure. The near IR pulsed laser irradiation of Fe-Si sample is a method of increasing the number of Weiss magnetic domains by laser annealing. The increase of Weiss domains number involves the decrease of relative magnetic permeability and magnetic remanence and the increase of coercive force in a Fe-Si sample.

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* Corresponding author: mary_voicu@yahoo.co.uk