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Influence of Fiber Laser Scribing on Magnetic Domains Structures and Magnetic Properties of NO Electrical Steel Sheets

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In this paper, microsecond pulsed fiber laser was used to study its effects on the resulting changes in magnetic domains structures, coercivity, and thermal stresses values in the area of interaction of laser beam with surface of high silicon non-oriented electrical steel sheets. The laminations for the cores used in electrical applications like motors, generators, and ballasts are manufactured by punching, mechanical cutting, or cutting by laser of coils of non-oriented fully processed electrical steels. The magnetic material close to the cutting edge is essentially influenced by these processes. Depending on the parameter, the magnetic properties can vary substantially. The experimental parameters including laser power variation in the range of 0–100 W, constant frequency of 500 Hz, and 20 μs pulse duration were used to perform four various laser scribing treatments. The results showed that compared to the laser untreated material with magnetic coercivity of 22 A/m, significant improvements, i.e., coercivity reductions were obtained after the laser treatments within laser power range of 12–50 W. The major effects responsible for the observed core losses improvements are related to optimal refinement of magnetic domains structures by applied laser treatments.

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PACS/topics: fiber laser, non-oriented electrical steel, magnetic domains, coercivity

1. Introduction

In general, electrical steels are widely used in the form of core-laminated products, e.g., in construction of power cores in generators and electromotors, thanks to their excellent power capacity which is also used in lamination form to carry magnetic flux in a variety of energy-efficient alternating current electrical machinery such as small and medium size transformers or electromotors for automotive. These steels are further categorized into cold rolled grain oriented (GO) and cold rolled grain non-oriented (NOES) steels. NOES steels of various grades contain silicon up to 3.5% without or with Al in some grades. During their magnetization under alternating current conditions, a part of electric energy is known to be consumed which is attributed to the existence of the so-called core losses.

Over the past several years, several techniques have been developed to reduce the domain wall spacing and thus also the losses by changing the magnetostatic or the magnetoelastic energy in electrical steel sheet. Mechanical scribing transverse to the sheet rolling direction is one method that has been found to be effective in reducing the domain spacing and lowering the losses. The more recent efforts to obtain desired benefits without aforementioned disadvantages have been focused on the use of pulsed laser scribing techniques. As a result, the magnetostatic or the magnetoelastic energy in the sheet changes, a thickness of the domain wall is reduced, and the residual tensile stress caused by the plastic deformation refines the domains. Consequently, the core loss is reduced. Domain refinement is commonly achieved by various laser sources (ruby laser, CO_2, Nd-YAG). The lines created by the laser beam can be spaced a few millimeters apart [1, 2]. The quick and powerful thermal effect produces a stress that creates subdomains inside the initial magnetic domains. Because of better polarization possibilities, using an Nd-YAG laser gives thinner domains after the laser beam interaction with the material and the loss decrease can reach 6–10% [3]. The interest in using lasers for domain refinement is evident for conventional laser sources [4, 5]. The work described in this paper was conducted to determine if a pulsed fiber laser could be used to reduce the coercivity in the NOES. The effects of fiber laser scribing on the microstructure, texture, magnetic domains, and coercivity are discussed.

2. Experimental

The specimens of Fe–1.4Si electrical steel of M540-50A grade with dimensions of $30 \times 10 \times 0.50$ mm^3 were used as experimental material. These samples were then annealed at 1073 K for 30 min in pure hydrogen atmosphere. The fiber laser scribing process was performed using experimental workstation TRUMPF 3003 with laser source TruFiber400 (Fig. 1). The dotted cavity matrix was formed in laser-irradiated sample by application of

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Fig. 1. Experimental workstation TRUMPF 3003 with laser source TruFiber400.

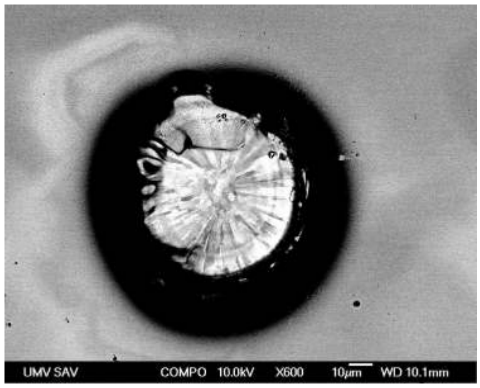

Fig. 2. Typical structures of magnetic domains within the 100 W laser pulse.

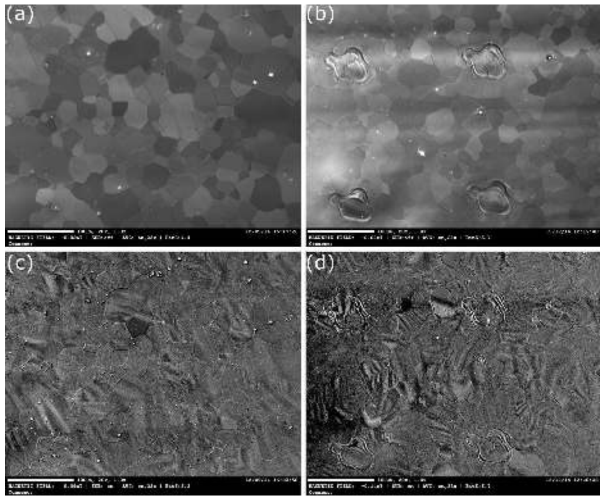

Fig. 3. KERR micrographs of M540-50A: (a) laser untreated, and laser treated (b) microstructure, (c) domain structure of laser untreated, and laser treated (d) specimen (200×200 μm, 50 W, 20 μs).

microsecond pulsed fiber laser scribing with laser power ranging from 12 to 100 W in air at room temperature. The intervals of laser spots were from 100×100 μm up to 300×300 μm and the diameter of single laser spot was about 20 μm. The prepared specimens were then electrolytically polished using Lectropol-5 electrolytic polishing machine in a solution of CH_3COOH and $HClO_4$ (20:1 per volume). The conditions of electrolytic polishing were: 49 V, 22 °C. The microstructure and morphology of laser treated surfaces were observed by scanning electron microscope (SEM) JEOL JSM-7000F. The coercivity was measured in DC magnetic field using "Oersted type" coercivity-meter KPS-1C. The magnetic domains structures were observed using magneto-optical Kerr-microscopy.

Crystallographic texture analysis was carried out using electron back scattered diffraction (EBSD) method in the plane oriented perpendicular to transverse direction. The EBSD patterns were detected by "Nordlys-I" EBSD detector. The obtained crystallographic data were processed using the CHANNEL-5, HKL software package.

3. Results and discussion

Figure 2 shows typical structure of magnetic domains within the 100 W laser pulse. Clear fragmentation of magnetic domains is observable within the area of the laser spot.

The Kerr micrographs of M540-50A for the laser untreated and laser treated material states are shown in Fig. 3. From the microstructure shown in Fig. 3a, the average grain size was estimated to be ≈ 42 μm. Figure 3b shows laser scribing effects resulting in plastic deformation near ablation craters caused by the laser pulse energy. Due to the plastic deformation, there is a generation of heat-affected zone (HAZ) of the Gauss shape. Magnetic domains structures of laser untreated and laser treated specimens are shown in Fig. 3a and b, respectively. It can be clearly seen that laser treatment caused obvious fragmentation and refinement of magnetic domains, compared to original magnetic domains structure of the laser untreated specimen. The soft magnetic characteristics, i.e., the coercivity values of individual samples were measured using a direct current (DC) coercivity measurement device.

From Fig. 4 it can be clearly seen that the relative change of coercivity values depend not only on the laser pulse power but also on the interval of laser pulses spots.

Clear improvements of soft magnetic properties (i.e., coercivity reduction) occur at lower values of laser pulse power. It has been generally accepted that the decrease of static hysteresis losses only appears if weak defects are produced. This behavior, i.e. the reduction of the coercive force and the power losses by the introduction of crystal defects, is known as the Brown paradox [6]. The influence of the pulses interval is not completely understood at present point of our investigation and it will be studied in more detail in our future studies. In general, during laser scribing, rapid heating and cooling of the material takes place. Rapid heating and cooling is the cause of thermal stresses, which are considered

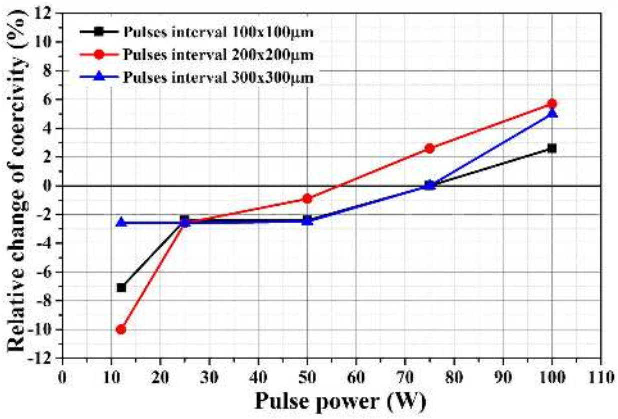

Fig. 4. The dependence of relative change of coercivity on the laser pulse power and pulses interval.

harmful on the magnetic properties of the material. On the other hand, the high temperatures involved in the laser scribing process may cause a magnetic domain refinement near the HAZ edge which is beneficial for the magnetic properties. The hindering and pinning effects are linked to the value of the anisotropy, which means that the coercivity tends to increase with the strength of anisotropy effects. In order to have a low coercive field the NOES should be free of precipitates, voids, and lattice defects. In addition, they should have a low density of grain boundaries and a favorable distribution of grain orientations. Also, if one of the grain easy axes is aligned to the applied field direction, a reduced value of the coercivity could be obtained [7, 8]. Interaction of laser radiation with the surface of M540-50A caused the HAZ regions creation, which have the same (001) orientation of closure magnetic domains of each grain (Fig. 3d). In our present investigation, only DC coercivity values have been measured because the determination of core loss (W/kg) would require bigger-sized samples that were not available. However, the obtained coercivity values represent strong indicative information about its magnetic properties in DC conditions. Both, Fig. 5a and Fig. 5b, show the microstructures of M540-50A in vicinity of laser pulse HAZ visualized by classical SEM imaging and EBSD inverse pole figure (IPF) mapping, respectively.

From Fig. 5 it is evident that the IPF map was recorded within microstructural region including the grains affected by laser beam with characteristic non-oriented texture. Thus, it is clearly visible that the laser scribing did not have any significant influence on the sharpness of the texture. In the case of laser modified NOES, the lower power density has desirable influence on the coercivity values, because the applied method does not damage the crystallographic texture of the material (Fig. 5b) and it does not generate supplementary pinning centers (Fig. 3d). It can be concluded that for laser modified samples with higher laser energies, the increase of the laser pulse energy density causes an increase of the coercivity. The lower laser energies promote a positive influence of the HAZ on soft magnetic properties, i.e., the coercivity values reduction (Fig. 4). The refined magnetic domains (Fig. 2) within the each laser pulse spot can potentially contribute to the coercivity lowering. However, at present point of investigation, it is not yet understood which mechanism dominates over the other. Nevertheless, the results obtained in present investigation by using fiber laser source, aiming at magnetic property modification, revealed that the low power laser modified samples of NOES steel sheets exhibited clearly reduced coercivity values, compared to the original material without laser modification.

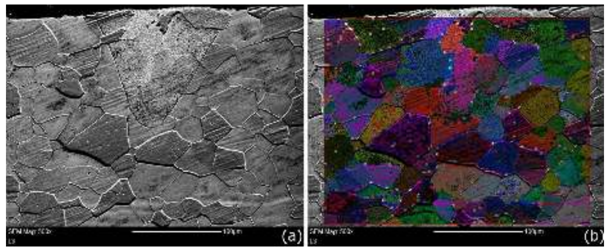

Fig. 5. Cross-sectional microstructures in vicinity of fiber laser induced HAZ regions in M540-50A visualized by: (a) conventional SEM imaging, (b) EBSD-IPF mapping (50 W,20 μs).

4. Conclusions

The present study was focused on investigation of the effects of pulse fiber laser scribing on magnetic domains structures and soft magnetic properties of non-oriented electrical steel sheets. It has been revealed that the applied laser scribing of the surface of investigated steel by pulse-periodic laser treatment resulted in changes of the coercivity values as a consequence of changes of magnetic domain structures. At lower laser power values (12–50 W), the soft magnetic properties were improved, i.e., the coercivity values were lowered. In contrast, at higher laser power, the coercivity values were increased. The used laser scribing treatments did not cause any significant changes in the crystallographic texture of the studied material. At the lowest laser power of 12 W, 10% decrease of coercivity was observed, compared to the laser untreated material. Such a significant reduction of coercivity in NOES provides promising opportunity for improvement of efficiency of various electrical machines.

Acknowledgments

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References

[1] T. Iuchi, S. Yamagushi, T. Ichimaya, M. Nakamura, T. Ishimoto, K. Kuroki, *J. Appl. Phys.* **53**, 2410 (1982).

[2] M. Daniels, *Phys. World* **1**, 33 (1988).

[3] T. Wada, T. Nosawa, T. Iuchi, N. Nakamura, *Nippon Steel Technical Report* 1983, 21 June, 263.

[4] J.-F. Coutouly, F. Breaban, P. Vantomme, P. Deprez, A. Deffontaine, *Adv. Eng. Mater.* **3**, 247 (2001).

[5] R. Gurusamy, P.A. Molian, *J. Laser Appl.* **9**, 147 (1997).

[6] B. Weidenfeller, W. Riehemann, *J. Magn. Magn. Mater.* **292**, 210 (2005).

[7] F. Fiorillo, *Measurement and Characterization of Magnetic Materials*, Elsevier Academic Press, Amsterdam 2004.

[8] A. Hubert, R. Schäfer, *Magnetic Domains*, Springer Verlag, 1998.