Arch. Metall. Mater. **69** (2024), 1, 381-387

DOI: https://doi.org/10.24425/amm.2024.149105

K. ŚCIBISZ[1,2*], J. KRAWCZYK[3]

MAGNETIC PROPERTIES OF Fe-Si ELECTRICAL STEEL AFTER LASER SCRIBING

Improvement of magnetic properties of electrical steel can be achieved by reduction the size of magnetic domains. The application of local stresses through laser scribing leads to reduced core losses. In order to determine the effect of laser refinement conditions of magnetic domains on the properties of the soft magnetic material, four samples with a thickness 0.23 mm were refined. The refinement of each sample was carried out using different line energies of the laser beam. Estimation of the magnetic domain size was performed using the Jeffries method, the magnetic viewer was used to reveal the domain structure. The measurement of the magnetic properties was performed at a frequency of 50 Hz and an induction of 1.5 T. The analyzed results presented in this work indicate impact of laser refining on magnetic properties of grain oriented electrical steel depending on used laser beam energy.

Keywords: Grain-oriented electrical steel; magnetic domain; laser scribing; magnetic properties; Barkhausen's noises

1. Introduction

The evaluation of the magnetic properties of grain-oriented Fe-Si steel subjected to generically directed field comes strongly into play when dealing with applications transformers and large rotating machines [1]. Line frequency transformers are the most important components of a power system, which transmit power between generation and distribution systems. The increasing global demands for efficient electrical power generation and distribution equipment are strong drivers for the development of steels with lower magnetic losses and higher permeability. Low core loss of iron, high magnetic flux density, low magnetostriction, high permeability and high saturation magnetization are key properties required for electrical steel. Grain oriented electrical steel (GOES) exhibit excellent magnetic properties longitudinally to their rolling direction, as a soft magnetic material are used mainly as a core for transformers [2-4]. The manufacturing of grain-oriented silicon steel require careful control of thermomechanical processing in order to generate desired microstructure and texture [5]. The processing steps and their parameters are adjusted to get at the end a Goss texture for excellent magnetization behavior and a large grain size with a sufficient number of movable domain walls [6]. Presence of the crystallographic texture {110}<001> where the easiest magnetization direction <001> is parallel to the magnetic field direction and sheet surface allows to minimize watt losses. Currently, the desirable Goss texture is obtained via a complicated processing scheme involving continuous casting, reheating, rough hot rolling, finish hot rolling, normalization, cold rolling, decarburization annealing and secondary recrystallization annealing. During the high temperature annealing small precipitates, also called inhibitors, play a crucial role in the inhibition of the grain growth and the development of a sharp Goss texture which evolves completely after the high temperature annealing and the grain oriented silicon steel with a good magnetic properties ($B_8 = 1.94$ T, $P_{1.7/50} = 1.3$ W/kg) can be prepared [7-11]. Over the past 90 years, magnetic properties of grain-oriented electrical steel have been dramatically improved. This has been achieved mainly by three technologies: improvement of {110}<001>alignment, development of thinner-gauge product with a thickness of 0.23 mm, and establishment of magnetic domain refining techniques [12,13]. Pulsed laser processing for domain's refinement is a recent technology implemented on an industrial scale, it is easily applicable to the production line of the silicon steel due to noncontact technique [14,15]. Silicon content, thickness, impurities, resistivity, permeability and domain structure of the steel significantly influences on core loss. Core loss consist of two components: hysteresis loss and apparent eddy current loss which is combination of classical eddy current loss and domain-dependent eddy loss.

---

[1] ARCELORMITTAL POLAND S.A. UNIT IN KRAKOW, TADEUSZA SENDZIMIRA 1 STR., 31-752 KRAKOW, POLAND
[2] AGH UNIVERSITY OF KRAKOW, FACULTY OF METALS ENGINEERING AND COMPUTER SCIENCE, AGH DOCTORAL SCHOOL, AL. MICKIEWICZA 30, 30-059 KRAKOW, POLAND
[3] AGH UNIVERSITY OF KRAKOW, FACULTY OF METALS ENGINEERING AND COMPUTER SCIENCE, AL. MICKIEWICZA 30, 30-059 KRAKOW, POLAND

* Corresponding author: scibisz@agh.edu.pl

The laser scribing reduces the core loss of 3% Si–Fe, because sub-domains induced by scribing produce many active domain walls which reduce the eddy current loss responsible for degradation of magnetic properties, caused by the generation of large amounts of heat [16-18]. The magnetic domains of GOES consist of two components: 180° main domains and 90° surface closure domains. Eddy-current losses monotonically decrease with decreasing 180° wall spacing and increase with increasing amount of 90° domains [18]. In order to reduce the size of magnetic domains local tensile stresses can be applied on sheet surfaces. The use of local tensile stresses along the rolling direction on the surface of GOES sheets reduces the size of basic 180° magnetic domains by changing the magneto crystalline energy (magnetic anisotropy) of the material [19]. In this paper impact of laser scribing as a method of magnetic domain refinement of GOES on magnetic properties has been presented. These studies allowed to determine the effect of one of the parameters of the laser refining process on the change of: domain structure, Barkhausen magnetic noise, lossiness, magnetic field strength of magnetization, coercivity and remanence, which shape the magnetic properties of the final product.

2. Materials and methods

This study was conducted using conventional grain oriented electrical steel M95-23P (high permeability (HiB) steel contains approx. 3% Si) in accordance with PN-EN 10107. It is a ferritic steel with BCC structure. The material was subjected to the process of refining of magnetic domains. Using an Nd: YAG laser, the magnetic domains of four material samples were refined with a thickness of 0.23 mm. Refining of each sample was carried out using different linear energy of the P_L laser beam. The parameters of the conducted experiment are shown the in the TABLE 1.

TABLE 1

Laser refining parameters of conventional grain-oriented electrical steel

Sheet No.	Distance between laser beam interaction areas [d_L], mm	Line speed [V], m/min	Linear energy of the laser beam [P_L], J/m
1	7	30	55
2	7	30	45
3	7	30	35
4	7	30	25
5	Reference sample – not refined		

3 samples were cut according to Fig. 1. from each refined sheet. Samples were tested in 2 magnetization directions: [110] and [100]. Measurement of magnetic properties in the direction of magnetization [110] was performed for the sample cut perpendicularly to the rolling direction, measurement of magnetic properties in the direction of magnetization [100] was performed for the sample cut parallel to the rolling direction. Measurement of Barkhausen magnetic noise in the direction of magnetization [110] and [100] was performed for the sample cut perpendicularly to the rolling direction. A Brockhaus Measurements device was used to measure the magnetic properties of the soft magnetic material. The measurement was performed at a frequency of 50 Hz and an induction of 1.5 T. Barkhausen magnetic noise was also measured using a STRESSCAN 500°C. The size of magnetic domains was estimated using Jeffries' method after revealing the domain structure by means of magnetic effects viewer presented on Fig. 2.

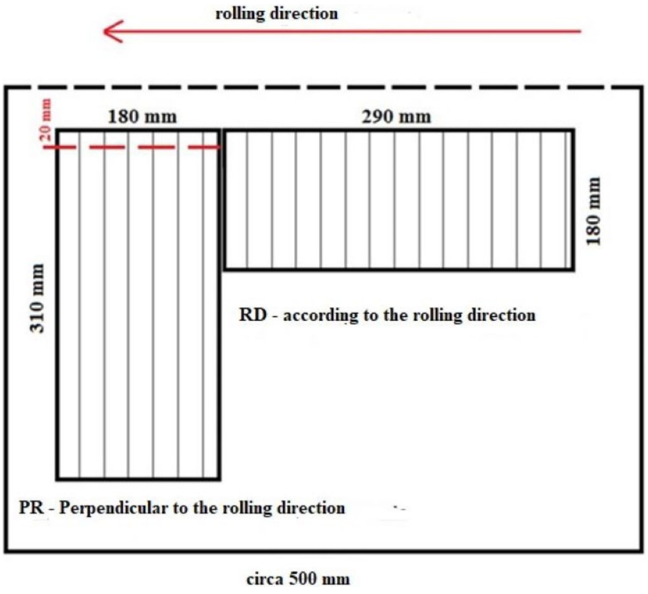

Fig. 1. Schematic of sample preparation for testing

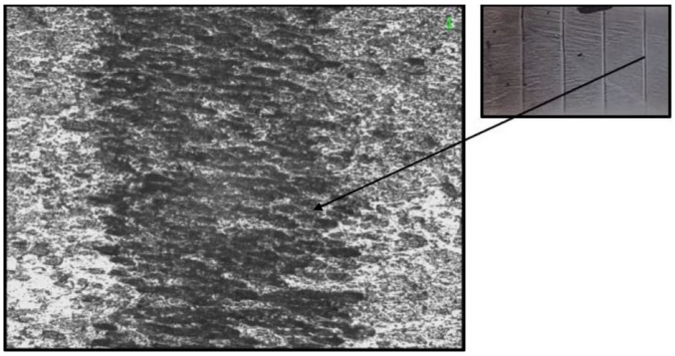

Fig. 2. Effect of the laser beam on the surface of the material sheet number 1 (etched sample without electrical insulating coating – image on the left side, the imaging location with electrical insulating layer and magnetic viewer coated surface – image on the right side)

3. Results and discussion

The power of the laser beam used in the laser refining process of a transformer sheet affects the magnetic properties of the processed material. The depth of refining increases as the laser beam power increases (Fig. 3). Therefore, in view of the depth of refining, the magnetic properties of the material are also expected to be affected.

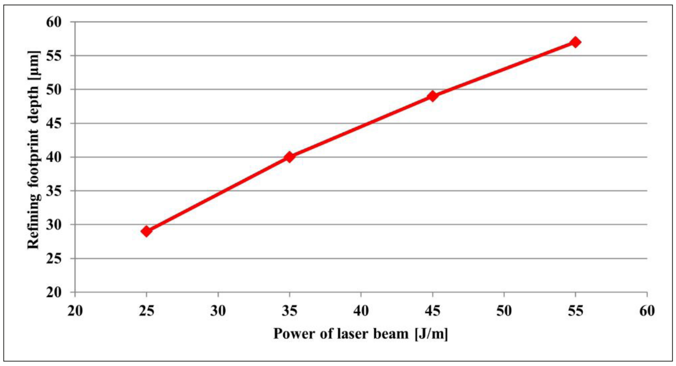

Fig. 3. Dependence of refining depth on laser beam power

Observation of the metallographic specimens using a light microscope made it possible to characterize and assess the microstructure of the material studied. Two zones, described in red and green, were distinguished (Fig. 4). The zone marked in red shows the depth of the laser beam, the green line shows the depth of the stresses interaction. The range of stress interactions was determined by the range of slip bands visible on the metallographic examination. The red line defines the range of slip bands occurring in more than one system and the green line defines the limit of visible shear bands finally occurring in one system.

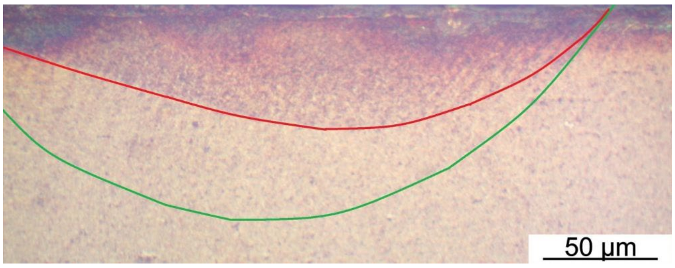

Fig. 4. Microstructure with marked zones of refining impact after application of a 55 J/m laser beam

A comparison of the images in Fig. 5 and Fig. 6 shows the difference between the effects associated with laser refining (Fig. 5) and the grain boundary image (Fig. 6). This comparison shows that laser refining does not introduce new grain boundaries because no such effect is seen in the laser refining area (Fig. 5).

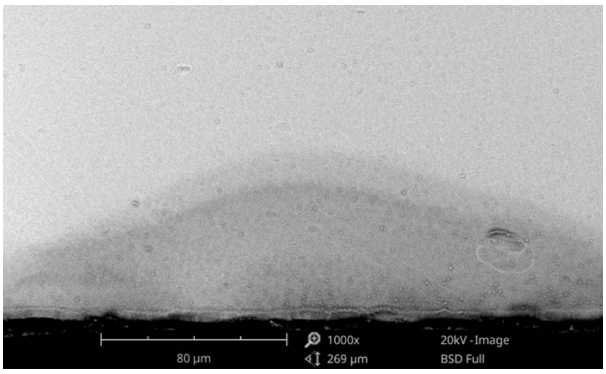

Fig. 5. Microstructure of sample No. 1 at the laser refining site. Laser beam energy applied 55 [J/m] – SEM

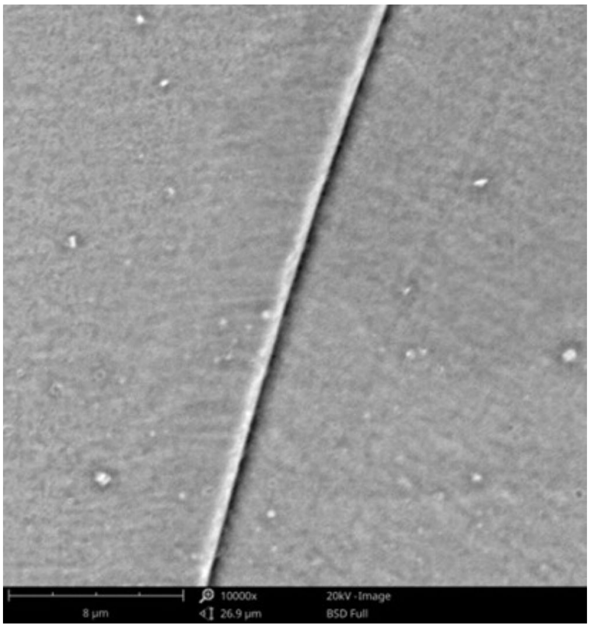

Fig. 6. Microstructure of sample No. 2 (laser beam energy applied 45 [J/m]) – grain boundary – SEM

3.1. Results of macro and microscopic observations of sheet metal surfaces

Macroscopic observations using magnetic viewer allows to evaluate the size of magnetic domains (Fig. 7) and grain size.

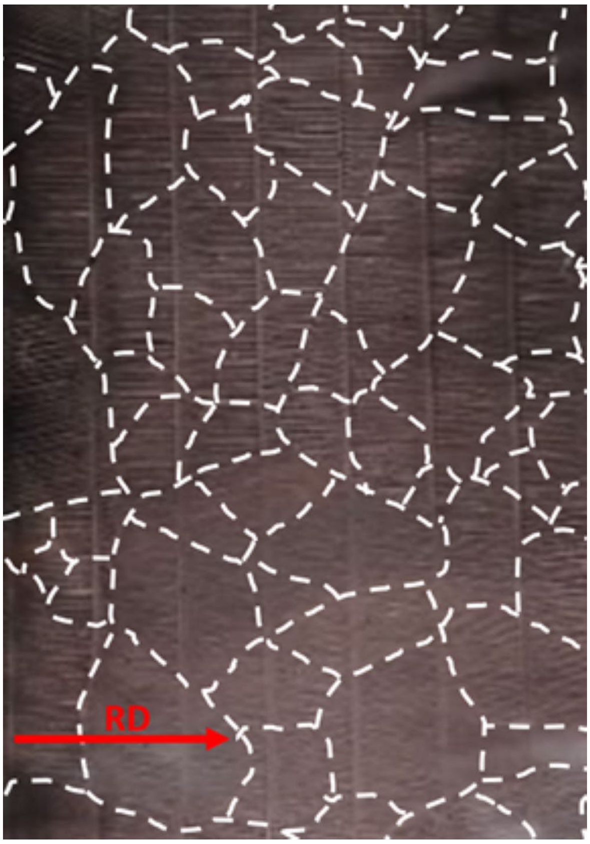

Fig. 7. Comparison of grain boundaries and domain boundaries by magnetic viewer method – sample No. 1

It can be observed that the laser processing traverse performed results in the separation of domains whose walls are perpendicular or nearly perpendicular to the rolling direction, that is, the direction of easy magnetization. The size of the magnetic domains was estimated for the samples treated with the laser beam in relation to the applied laser beam power (Fig. 8). It can be observed that the increase in laser beam energy leads to fragmentation of magnetic domains, which results mainly from a decrease in distance between Bloch 180° walls.

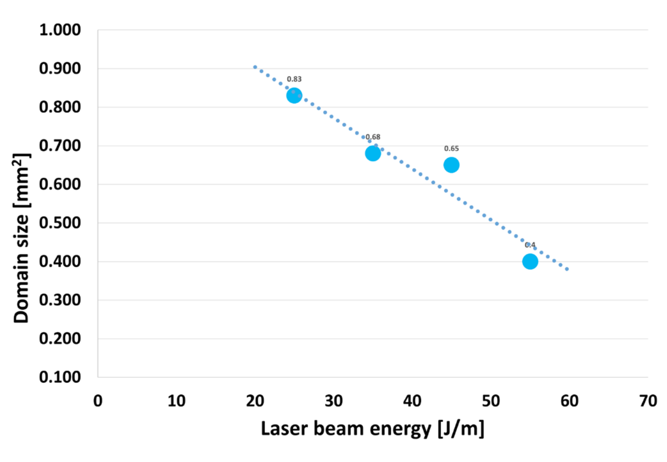

Fig. 8. Change in the size of magnetic domains as a function of laser beam energy

Laser refining results the introduction of stress which will cause an increase in coercivity and decrease in MP, the opposite effect is the fragmentation of the domain structure an increase in MP and a decrease in coercivity. This opposing effect means that up to a certain moment laser refining has a beneficial effect, while at a certain point the stress effect takes over the role. Fragmentation of magnetic domains is desirable and shows a positive effect on magnetic properties up to a certain point.

3.2. Results of Barkhausen magnetic noise analysis

The high level of magnetic Barkhausen noise determined by the MP parameter can be related to the easy movement of Bloch walls. The device used in the study allows determining the depth from which the Barkhausen magnetic noise level is analyzed. Since the sheet is characterized by a thickness of 0.23 mm, taking the range analyzed at 0.7 mm, the entire cross-section of the sheet was analyzed. The range of the impact of the laser beam's linear energy on the microstructure depends on the energy used. Taking into account that used laser beam energy may not cover the entire cross-section of the sheet, in addition, it was decided to also perform tests for an area with a depth of less than 10% of the sheet thickness, i.e. from a layer as deep as 0.02 mm. Analyzing the entire cross-section of the sheet, it was found (as expected) that the Barkhausen magnetic noise level (MP parameter) is higher for measurements in the direction in line with the rolling direction, which corresponds to the easy magnetization direction [100]. In the transverse direction (TD), which is parallel to the crystallographic direction of type <110>, the Bloch walls are more difficult to move, as evidenced by lower values of the MP parameter (Fig. 9).

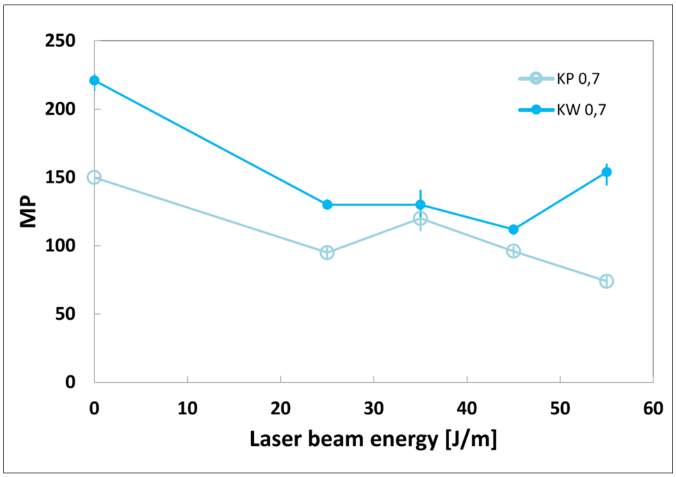

Fig. 9. Effect of refining on the MP parameter obtained for the entire cross-section (analyzed range of depth 0.7 mm) of the plate in the transverse (TD) and longitudinal (LD) direction to the rolling direction

3.3. Analysis of magnetic loss

The magnetic loss of the test material in the longitudinal direction is significantly lower than in the transverse direction (Fig. 10). Refining magnetic domains has a beneficial effect on reducing magnetic loss. Within the range of measurements performed, the lowest loss, equal to 0.60 W/kg, was obtained for the linear laser beam energy of 35 J/m. Further increasing the linear energy of the laser beam raises the lossiness but it is still significantly lower than the unrefined sheet where it reached a value of 0.73 W/kg.

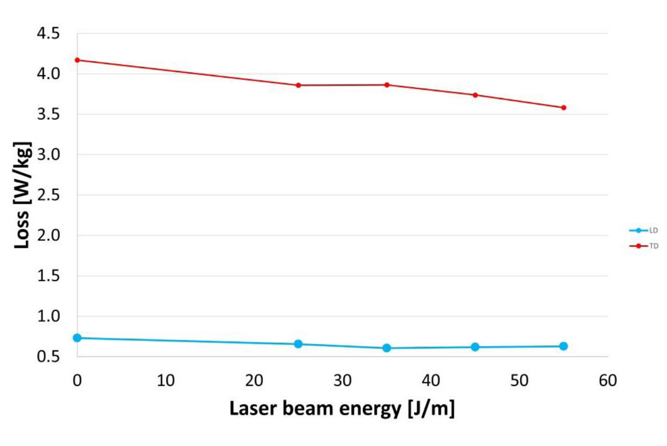

Fig. 10. Losses [W/kg] as a function of the applied laser beam line energy [J/m]

3.4. Analysis of magnetic field strength

While refining, favorably influenced the reduction of the lossy in the easy magnetization direction, it has an unbeneficial effect on magnetic field strength required to magnetize the material to the 1.5 T level (Fig. 11, Fig. 12).

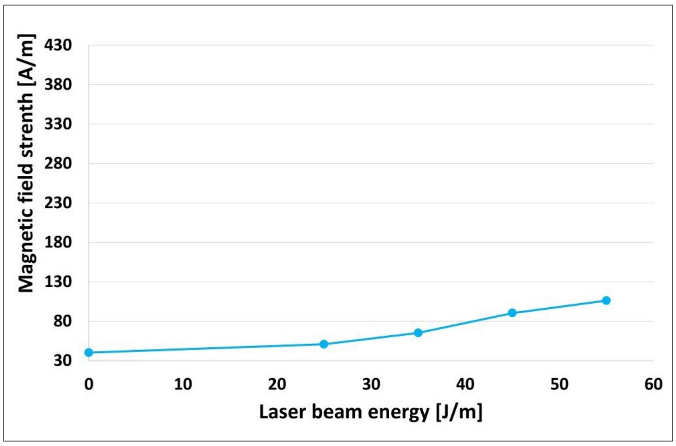

Fig. 11. Magnetic field intensity [A/m] required to magnetize the sample depending on the applied laser beam line energy [J/m] – longitudinal direction

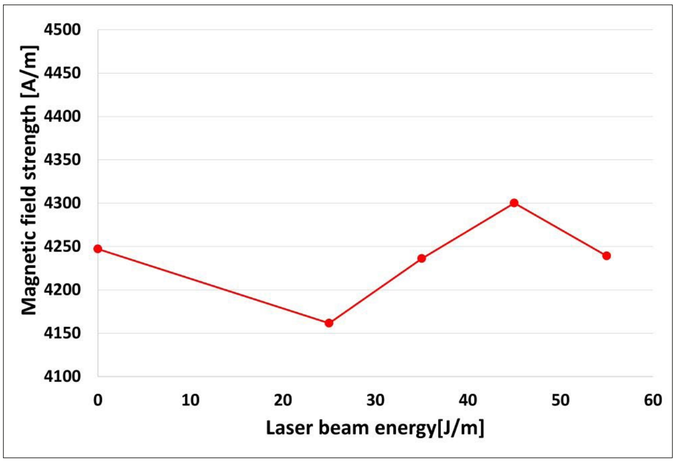

Fig. 12. Magnetic field intensity [A/m] required to magnetize the sample depending on the applied laser beam line energy [J/m] – transverse direction

3.5. Coercion analysis

Evaluating a soft magnetic material, it is most common to relate this evaluation to the value of coercivity which represents the intensity of the magnetic field required for demagnetization. In the case of soft magnetic materials, the field strength should be lower than the material's own field strength, which has a demagnetizing effect on the material itself. The refining process for both the easy magnetization direction and the transverse direction reduces the values of coercivity [Fig. 13, Fig. 14].

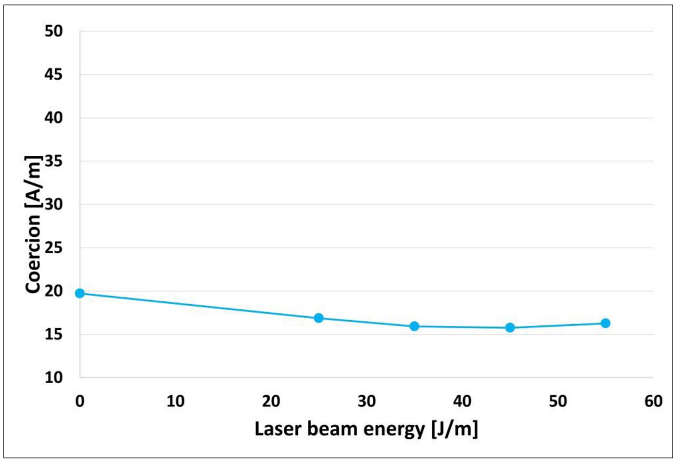

Fig. 13. Coercion [A/m] vs. linear energy of the laser beam [J/m] – longitudinal direction

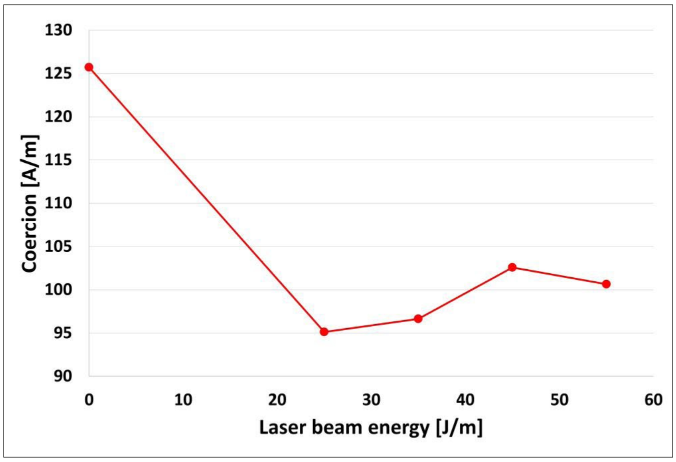

Fig. 14. Coercion [A/m] vs. linear energy of the laser beam [J/m] – transverse direction

3.6. Remanence analysis

The effect of sheet orientation and the refining process on remanence is shown in the graphs in Fig. 15 and Fig. 16.

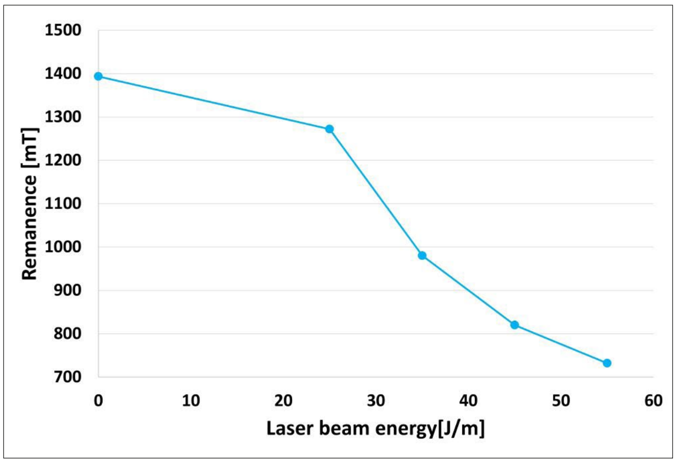

Fig. 15. Remanence [mT] versus laser beam line energy [J/m] – longitudinal direction

As can be seen, the direction of easy magnetization is distinguished by a significantly higher remanence value. Moreover, the laser refining process causes a decrease in remanence with an increase in the linear energy of the laser beam, both in the easy magnetization direction parallel to RD and in the transverse direction of the sheet.

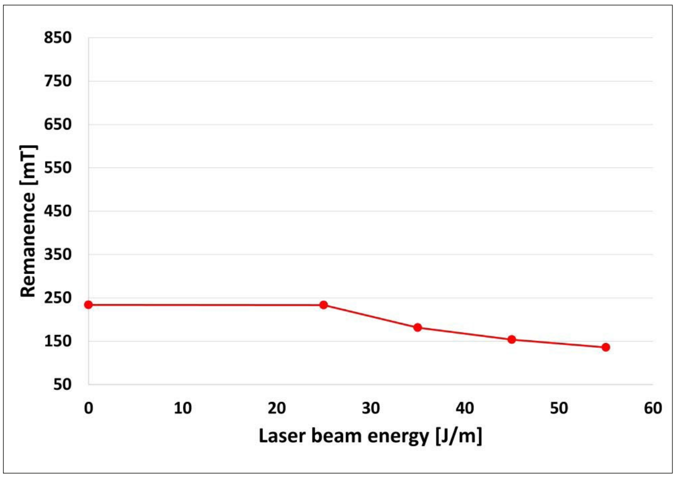

Fig. 16. Remanence [mT] versus laser beam line energy [J/m] – transverse direction

4. Conclusions

The analyzed results presented in this work indicates impact of laser refining on magnetic properties of GOES depending on the laser beam energy used. The main conclusions can be formulated as follows:

- The increase in the linear energy of the laser beam leads to the fragmentation of magnetic domains.
- Analyzing the entire cross-section of the sheet, the Barkhausen magnetic noise level (MP parameter) is higher for measurements in the rolling direction (RD), which corresponds to the easy magnetization direction [100].
- The loss in the rolling direction are significantly smaller than in the direction transverse to the rolling direction.
- Refining of magnetic domains in the rolling direction reduces the loss level of electrical steel.
- The longitudinal direction, and therefore the rolling direction, is a direction of easy magnetization requiring about two times less magnetic field strength to magnetize.
- Refining in the easy magnetization direction increases the magnetic field strength required to magnetize the material to the 1.5 T level.
- The refining process for both the easy magnetization direction and the transverse direction reduces the coercivity values. The coercivity in the case of the easy magnetization direction is significantly smaller (by almost an order of magnitude) compared to the coercivity in the transverse direction (type [110]).
- The direction of easy magnetization is characterized by a significantly higher remanence value.
- The laser refining process, along with an increase in the linear energy of the laser beam, results in a decrease in remanence in both the easy magnetization direction and the transverse direction of the sheet.

Acknowledgments

The Ministry of the Education and Science financed this work within the 5th edition of the Implementation PhD programme. The authors of this study would like to thank Mr. Mateusz Pudełek for help in this research.

REFERENCES

[1] C. Appino, E. Ferrara, F. Fiorillo, C. Ragusa, O. De la Barrière, Static and dynamic energy losses along different directions in GO steel sheets. Journal of Magnetism and Magnetic Materials **500** (2020).
DOI: https://doi.org/10.1016/j.jmmm.2019.166281

[2] A.J. Moses, Energy efficient electrical steels: Magnetic performance prediction and optimization. Acta Materialia Inc. Published by Elsevier **67** (2012).
DOI: http://dx.doi.org/10.1016/j.scriptamat.2012.02.027

[3] B. Sai Ram, A.K. Paul, S.V. Kulkarni, Soft magnetic materials and their applications in transformers. Journal of Magnetism and Magnetic Materials **537** (2021).
DOI: https://doi.org/10.1016/j.jmmm.2021.168210

[4] Y. Huh, K. Jung Hong, M. Soo Han, S. Kang, Formation mechanism and microstructure of a forsterite film in grain-oriented electrical steel. Thin Solid Films **752** (2022).
DOI: https://doi.org/10.1016/j.tsf.2022.139258

[5] A. Nadoum, F. Robinson, S. Birosca, On the correlation between magnetic domain and crystallographic grain orientation in grain oriented electrical steels. Journal of Magnetism and Magnetic Materials **494** (2020).
DOI: https://doi.org/10.1016/j.jmmm.2019.165772

[6] S. Fortunati, S. Cicale, J. Schneider, A. Franke, R. Kawalla, Developments in the Field of Electrical Steels over the Last Years. Proc. 7th International Conf. Magnetism and Metallurgy WMM18, June Rome, Italy (2016). ISBN 978889000330

[7] A.L. Etter, T. Baudin, R. Penelle, Influence of the Goss grain environment during secondary recrystallisation of conventional grain oriented Fe-3%Si steels. Scripta Materialia **47** (2002).
DOI: https://doi.org/10.1016/S1359-6462(02)00189-6

[8] J.A. Sandoval Robles, A, Salas Zamarripa, M.P. Guerrero Mata, J. Cabrerab, Texture evolution of experimental silicon steel grades. Part I: Hot rolling. Journal of Magnetism and Magnetic Materials **429** (2017).
DOI: https://doi.org/10.1016/j.jmmm.2016.10.163

[9] Y. Wang, Y.X. Zhang, X. Lu, F. Fang, Y. Xu, G.M. Cao, Ch. Li, R.D.K. Misra, G. Wang, A novel ultra-low carbon grain oriented silicon steel produced by twinroll strip casting. Journal of Magnetism and Magnetic Materials **419** (2016).
DOI: https://doi.org/10.1016/j.jmmm.2016.06.036

[10] N. Bernier, C. Xhoffer, T. De Putte, M. Galceran, S. Godet, Structure analysis of aluminium silicon manganese nitride precipitates formed in grain-oriented electrical steels. Materials Characterizationa (2013).
DOI: https://doi.org/10.1016/j.matchar.2013.09.014

[11] Y. Wang, Y. Xu, Y.X. Zhang, F. Fang, X. Lu, H.T. Liu, G.D. Wang, Development of microstructure and texture in strip casting grain oriented silicon steel. Journal of Magnetism and Magnetic Materials **379** (2015).
DOI: https://doi.org/10.1016/j.jmmm.2014.12.043

[12] Z. Xia, Y. Kang, Q. Wang, Developments in the production of grain-oriented electrical steel. Journal of Magnetism and Magnetic Materials **320** (2008).
DOI: https://doi.org/10.1016/j.jmmm.2008.07.003

[13] Y. Ushigamia, M. Mizokamia, M. Fujikuraa, T. Kubotaa, H. Fujiib, K. Murakam, Recent development of low-loss grain-oriented silicon steel. Journal of Magnetism and Magnetic Materials **254-255** (2003).
DOI: https://doi.org/10.1016/S0304-8853(02)00933-2

[14] T. Iuchi, S. Yamaguchi, T. Ichiyama, M. Nakamura, T. Ishimoto, K. Kuroki, Laser processing for reducing core loss of grain oriented silicon steel. Journal of Applied Physics **53** (1982).
DOI: https://doi.org/10.1063/1.330828

[15] M. Nesser, O. Maloberti, C. Pineau, J. Dupuy, J.P. Birat, J. Fortin, GOES's domain structure in the vicinity and on the lines post-laser treatment. Journal of Magnetism and Magnetic Materials **564** (2022).
DOI: https://doi.org/10.1016/j.jmmm.2022.170145

[16] K. S. Ryu, Y. Park, C. G. Kim, J. Ryu, D. Son, Core loss reduction by laser scribing in grain-oriented 3% Si–Fe under different magnetizing direction. Physica Status Solidi (A) **201** (2004).
DOI: https://doi.org/10.1002/pssa.200304662

[17] Y. Chen, L. Zhang, H. Sun, F. Chen, P. Zhang , X. Qu, E. Fan, Enhanced magnetic properties of iron-based soft magnetic composites with phosphate-polyimide insulating layer. Journal of Alloys and Compound 813 (2020).
DOI: https://doi.org/10.1016/j.jallcom.2019.152205

[18] S. V. Ponnaluri, R. Cerukuri, P.A. Molian, Core loss reduction in grain-oriented silicon steels by excimer laser scribing: Part I: experimental work. Journal of Materials Processing Technology 112 (2001).
DOI: https://doi.org/10.1016/S0924-0136(01)00573-8

[19] I. Petryshynets, F. Kováč, V. Puchý, M. Šebek, J. Füzer, P. Kollár, Magnetic losses reduction in grain oriented silicon steel by pulse and continuous fiber laser processing. AIP Advances 8 (2018).
DOI: https://doi.org/10.1063/1.4994191

[20] M.R. Jahangiria, H. Bayania, M. Ardestanib, M. Mehdizadeh, Core loss reduction in grain oriented silicon steel sheets by two-sided laser scribing in the presence of a magnetic field. Journal of Alloys and Compounds **891** (2021).
DOI: https://doi.org/10.1016/j.jallcom.2021.162080