AIP Advances

Magnetic properties deterioration of non-oriented steel due to laser cutting

Cite as: AIP Advances **13**, 025360 (2023); https://doi.org/10.1063/9.0000586
Submitted: 03 October 2022 • Accepted: 31 January 2023 • Published Online: 23 February 2023

Changgeng Zhang, Yan Zhang, Yongjian Li, et al.

COLLECTIONS

Paper published as part of the special topic on 67th Annual Conference on Magnetism and Magnetic Materials

openaccess

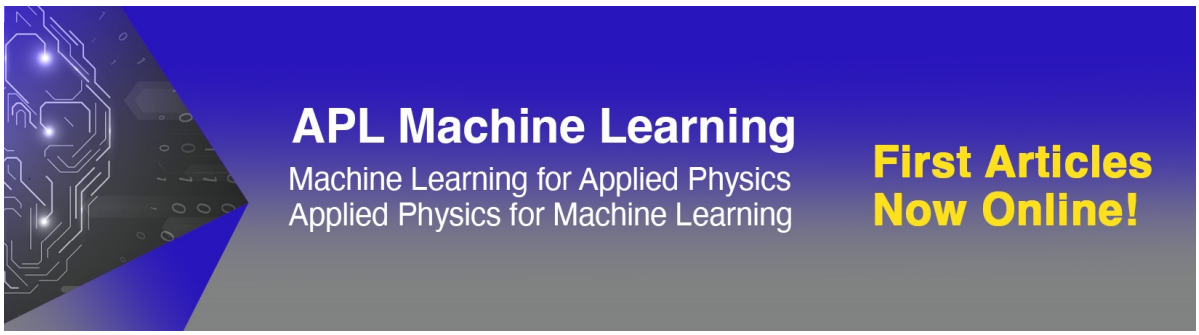
View Online Export Citation CrossMark

ARTICLES YOU MAY BE INTERESTED IN

Study of magnetic properties of electrical steels with different Si content considering the effect of temperature
AIP Advances **13**, 025044 (2023); https://doi.org/10.1063/9.0000578

A 24 nW 10-bit 10 kS/s ultra-low-power SAR ADC for biomedical devices
AIP Advances **13**, 025351 (2023); https://doi.org/10.1063/5.0138835

Anisotropy of losses in grain-oriented Fe–Si
AIP Advances **11**, 115208 (2021); https://doi.org/10.1063/5.0066131



AIP Publishing

© 2023 Author(s).

Magnetic properties deterioration of non-oriented steel due to laser cutting

Cite as: AIP Advances 13, 025360 (2023); doi: 10.1063/9.0000586
Submitted: 3 October 2022 • Accepted: 31 January 2023 •
Published Online: 24 February 2023

View Online Export Citation CrossMark

Changgeng Zhang,[1,2,a)] Yan Zhang,[1,2] Yongjian Li,[1,2] and Qingxin Yang[1,2]

AFFILIATIONS

[1] State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology, Tianjin 300401, China
[2] Province-Ministry Joint Key Laboratory of EFEAR, Hebei University of Technology, Tianjin 300401, China

Note: This paper was presented at the 67th Annual Conference on Magnetism and Magnetic Materials.
[a)] **Author to whom correspondence should be addressed:** changgeng.zhang@hebut.edu.cn

ABSTRACT

In the manufacturing process of electrical machines, laser cutting is widely used to produce the laminations of cores. The internal stresses introduced by the high-energy laser beam will lead to deterioration in the magnetic properties of the non-oriented silicon steels. To accurately predict the core losses of the electrical machines, it is important to analyze the deterioration degree and the deterioration mechanism of the non-oriented steel sheets caused by laser cutting. In this paper, first, the local magnetic properties of the non-oriented steel 35WW250 at different positions are measured under the alternating sinusoidal excitation, in which the degradation degree is evaluated based on the core loss from the macroscopic perspective. Second, from the microscopic perspective, the observed magnetic domain patterns at the edge and those evolutions under the excitation of the magnetic field are investigated. The experimental results demonstrate that laser cutting can lead to the magnetic degradation of the non-oriented steels with a transverse depth of 18 mm from the edge. Moreover, the laser cutting process leads to significant variations in the patterns of the magnetic domains at different positions. The magneto-optical observation and local magnetic measurement verified the effectiveness of the analytical method, which is of great significance for the evaluation and improvement of the processing technique of the silicon steels.

© 2023 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/9.0000586

I. INTRODUCTION

Facing the global energy crisis, the energy efficiency of electrical equipment has received extensive attention. Statistics indicate that electric machines are generally responsible for about 2/3 of industrial power consumption. The stator and rotor cores are generally made of non-oriented electrical steels due to their approximate magnetic isotropy.[1,2] Laser cutting is widely used in the processing of electrical steels with the advantages of non-contact and high cutting speed. However, a large number of studies have shown that the stresses induced by laser cutting on the electrical steel sheets significantly affect the magnetic properties at the edge, resulting in a non-negligible increase in core losses.[3,4] Therefore, it is crucial to analyze the deterioration degree and mechanism of magnetic properties after laser cutting to improve the efficiency of electrical equipment.

The laser cutting process degrades the magnetic properties of electrical steels, which will change the microstructure and magnetic domain pattern near the edge of the electrical steels.[5] The magnetic property deterioration due to laser cutting has been investigated previously. Researchers mostly use the single sheet tester to analyze the effect of cutting on the magnetic properties of materials.[6–8] The cutting quality of the samples is affected by cutting speed, laser frequency, pulse width, auxiliary gas and other factors, and the magnetic performance deteriorates more obviously as the number of cuts increases.[9–11] In addition, the laser cutting process involves melting and solidification, which will generate thermal stresses. The thermal stresses will produce domain pinning, leading to variations in the microstructure and magnetic domain patterns near the edge of the electrical steel sheets.[12–14] Therefore, the accurate measurement of the deterioration range of the magnetic properties caused by laser cutting and the analysis of the deterioration

mechanism of non-oriented steels are also subjects that need to be studied.

In this research, the deterioration zone of non-oriented electrical steel sheets caused by laser cutting is calculated and compared by the local magnetic characteristic test system. Then, based on the magnetic domain observation technology, the magnetic domain patterns at the edge and those evolutions under the excitation of the magnetic field are investigated.

II. MATERIALS AND METHODS

A. Sample preparation

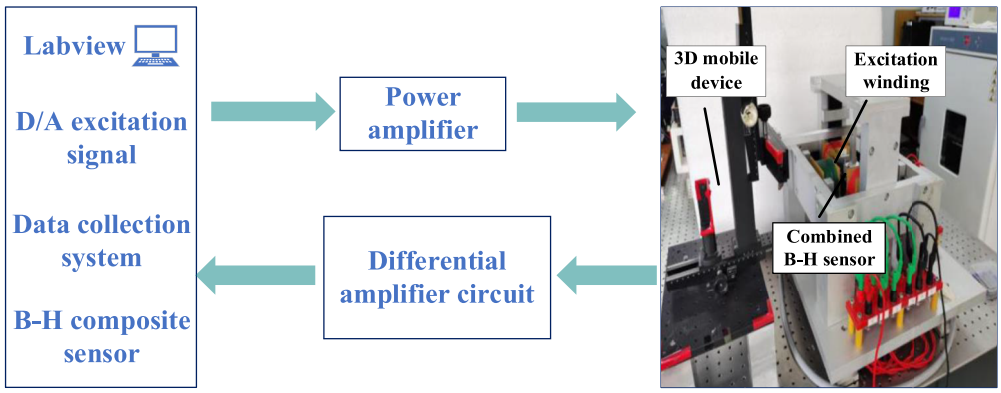
The samples are non-oriented (NO) 35WW250 steel sheets with 49.5 mm × 49.5 mm. The raw materials are annealed at 700 °C for 2 hours to relieve stresses induced due to prior processing and then cut by a high-power density laser beam along the rolling direction from the middle of the raw materials. The focused laser beam was directed at the magnetic materials resulting in the local melting of the steel. The physical parameters of the samples are listed in Table I.

B. Magnetic properties measurements

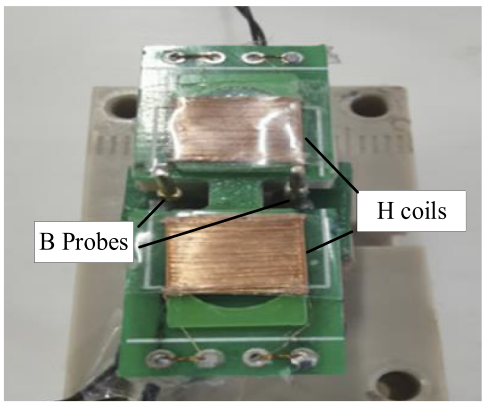
Based on the local magnetic property testing system, the local magnetic characteristic of the non-oriented steel sample near the edge is tested under sinusoidal excitation and shown in Fig. 1(a). The local magnetic characteristic test system is mainly composed of the signal generation system, data acquisition system, B-H signal

TABLE I. Physical parameters of the non-oriented steel samples.

Electrical steel samples	Length (mm)	Width (mm)	Thickness (mm)	Density (g/cm^3)	Processing method
35WW250	49.5	49.5	0.35	7.60	Laser cutting



(a)



(b)

FIG. 1. (a) Local magnetic characteristic testing system; (b) The combined B-H sensor.

© Author(s) 2023

acquisition system, high-performance power amplifier, multi-channel differential amplifier circuits and local magnetic characteristic tester.

The mobile B-H sensor with B probes and H coils is shown in Fig. 1(b). Considering the signal instability and other factors, the H coils are made 6 mm × 6 mm. The front and rear double H coils are used for H measurement, and the average value of the measurement results of the two coils is taken as the measurement result. The distance between the two probes is 7 mm.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Hysteresis loops

Under the excitation of 50 Hz frequency and magnetic flux density (B) of 1.6 T, the hysteresis loops at different positions along the rolling direction are shown in Fig. 2 (a). The laser cutting process deteriorates the magnetic properties, leading to the flattening of the hysteresis loops and the increase of the areas of the hysteresis loops. The required magnetic field strength H at the edge of the sample is larger than in the center of the sample when both are magnetized to the same magnetic flux density B. When the local B reaches up to 1.6 T, the applied H is 531 A/m in the center and 706 A/m in the zone 4 mm from the edge.

From the above analysis, it can be seen that the magnetic properties of the sample edge have been degraded by laser cutting. In order to quantitatively evaluate the range of the degradation of magnetic properties affected by the laser cutting, adjust the position knob of the three-dimensional mobile device to move the composite B-H sensor, so that the sensor is moved from the edge to the sample center gradually with a step of 2 mm until the measured local magnetic properties at different positions are basically consistent. Figure 2(b) compares the hysteresis loops at different distances from the edge. The closer to the edge, the worse the magnetic properties of the sample. The magnetic property in the zone within 18 mm from the edge is degraded significantly. Among them, the deterioration of magnetic properties is most obvious in the zone within 4 mm from the edge.

B. Loss characterization

The core losses of non-oriented steel sheets at different frequencies and locations are illustrated in Fig. 3. With the excitation frequency of 50 Hz and B of 1.4 T, the loss at 4 mm from the edge of the sample is 2.19 W/kg and the loss at the center of the sample is 1.84 W/kg, with a difference of 13.5%. With the excitation frequency of 200 Hz and B of 1.4 T, the core losses at the two locations are 15.91 W/kg and 11.01 W/kg, respectively, with a difference of 44.5%. As a result, from the macroscopic perspective laser cutting leads to a significant increase in the losses at the edge, and the core losses are positively correlated to the working frequency. As the working frequency increases, the losses caused by laser cutting change more drastically.

The core losses analysis was performed for the 35WW250 steel according to the conventional loss separation theory, assuming that the total core losses are a summation of hysteresis loss and dynamic loss.[15,16]

$$W = W_{\text{hyst}} + W_{\text{dyn}} = k_h B + k_{dyn} B^{\alpha} f^{\alpha-1} \tag{1}$$

where W_{hyst} is hysteresis loss, W_{dyn} is the dynamic loss. k_{h}, k_{dyn} and α are hysteresis, dynamic and exponential of fitting coefficients, respectively.

Figure 4 illustrates the influence of the edge hysteresis and dynamic loss of the sample when the sample is magnetized to be 0.8 T at 50 Hz. The hysteresis loss and dynamic loss both increase significantly. Compared with the central zone, the dynamic loss increases by 31.19% while the hysteresis loss increases by 23.88% at 4mm from the edge. After reviewing the pieces of literature about magnetic domain patterns of silicon steels, we find that the hysteresis loss of ferromagnetic materials is originated from the movement of magnetic domains, and the laser cutting process increases the resistance of magnetic domain movement and thereby increases the hysteresis loss. The residual stress component perpendicular to the edge also increases hysteresis loss.[8] The dynamic loss con-

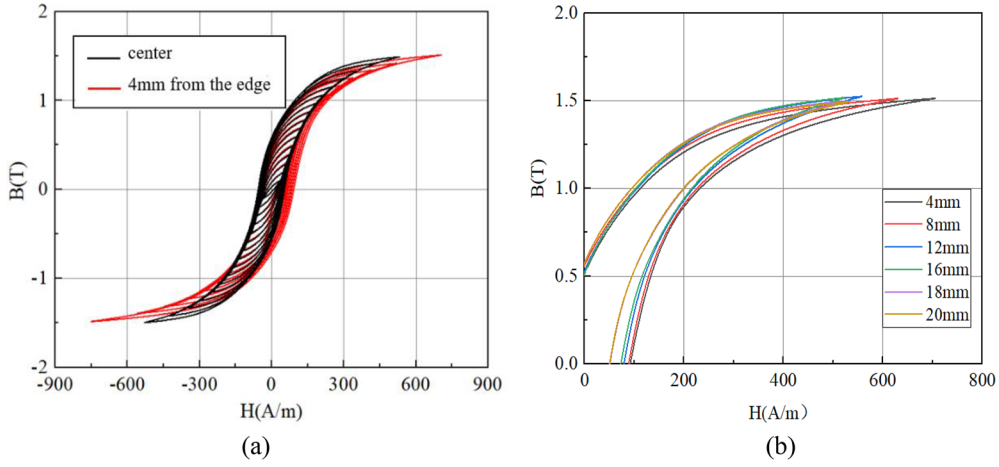


FIG. 2. (a) Hysteresis loops at the center and 4 mm from the edge; (b) Local hysteresis loops at different positions near the edge.

© Author(s) 2023

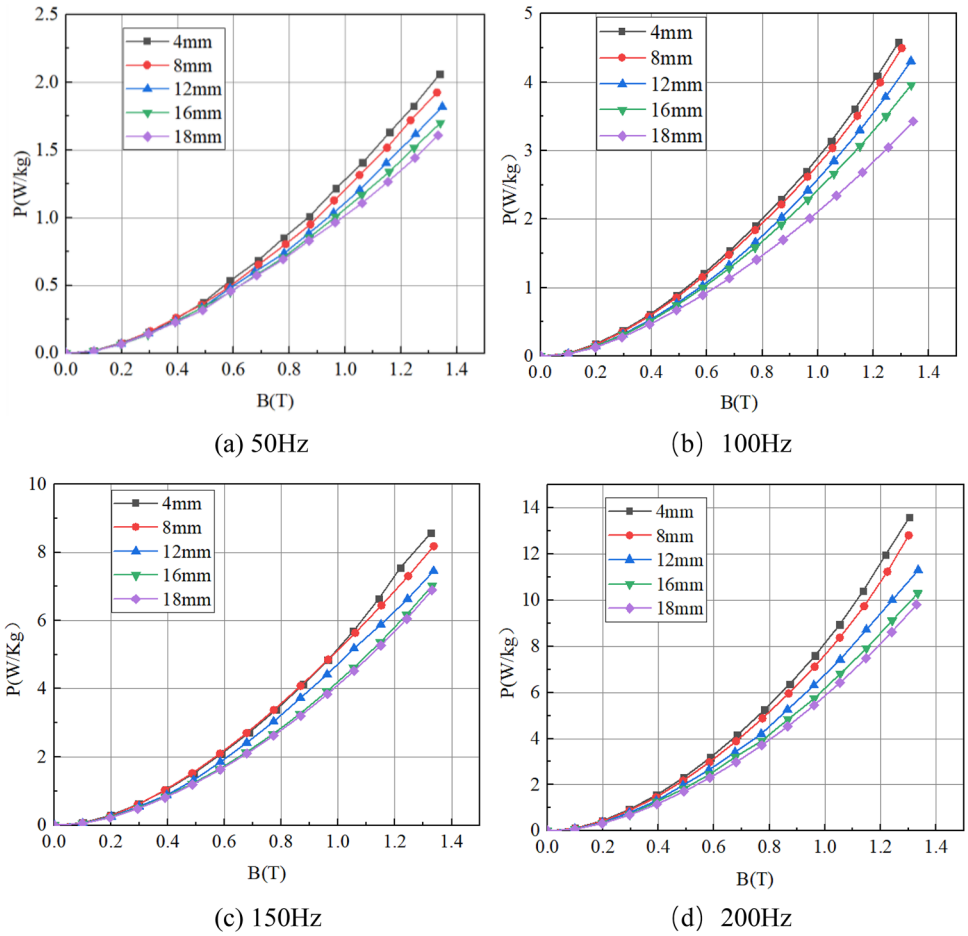


FIG. 3. Losses at different frequencies (a) 50 Hz, (b) 100 Hz, (c) 150 Hz, (d) 200 Hz.

sists of classical eddy current loss and the excess loss that is caused by the uneven distribution of magnetic domain patterns. The increase in domain width may also lead to an increase in dynamic loss.[17,18]

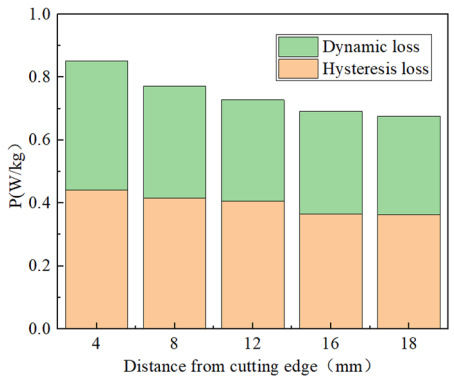


FIG. 4. Loss components at different positions near the edge with the excitation frequency of 50 Hz and B of 0.8 T.

C. Magnetic domain imaging

The laser cutting process causes an impulse heat source near the edge, resulting in thermal stress that finally changes the microstructure of the sample.[8] In this paper, the domain patterns of non-oriented steels at different magnetization states are captured and shown in Fig. 5. The cord-shaped magnetic domains are visible away from the edge in the unaffected zone whereas the domain patterns near the edge are evolved due to laser cutting.

According to the spatial distribution of the magnetic domain pattern, it can be roughly divided into three zones as listed in Table II. The first zone consists of obvious cord-shaped magnetic domain patterns, the second zone consists of large and wide domain patterns following irregular distribution of magnetic domain patterns, and in the third zone, the magnetic domain patterns are ambiguous to observe.

Figures 5(d)–(i) show the variations of the magnetic domain patterns at different locations with the applied magnetic field. As shown in the circular mark, the cord-shaped magnetic domain pattern in the central zone has a threshold value of 111 Oe, while the magnetic domain pattern at zone 2 has a threshold value of 311 Oe. The sample at the edge is more difficult to be magnetized compared with the central position. It can be explained that the laser cutting

© Author(s) 2023

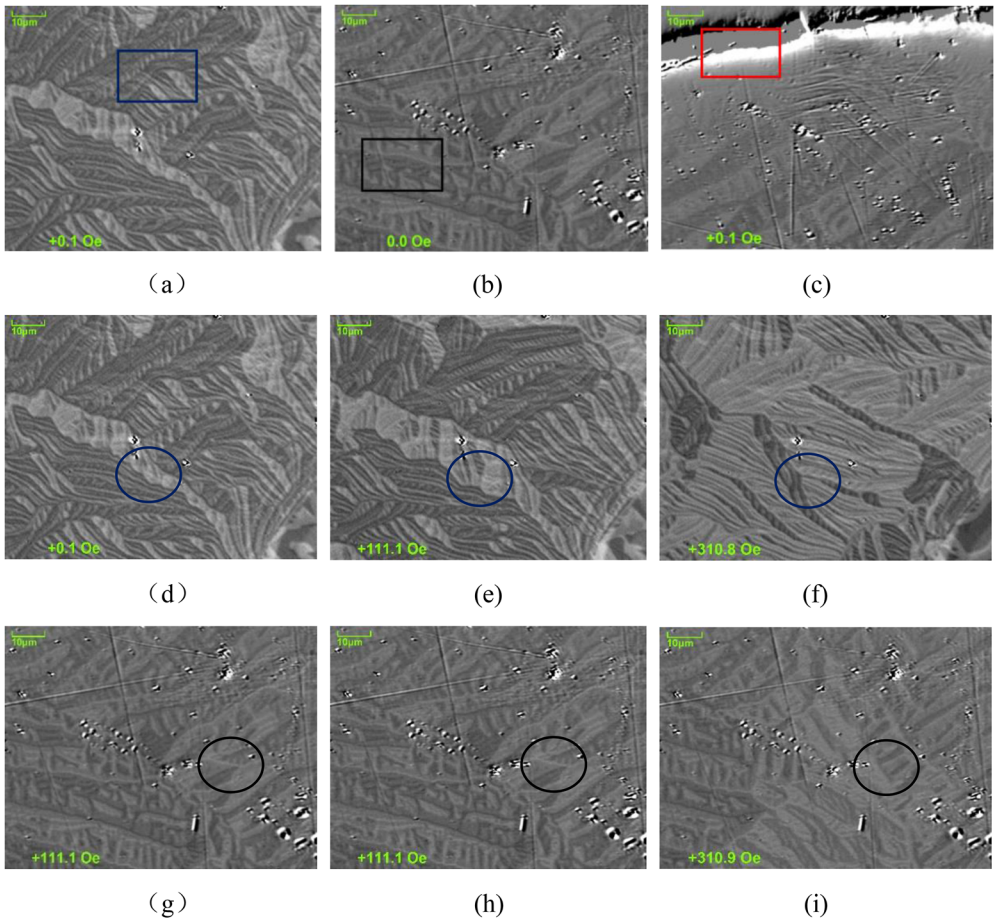


FIG. 5. Magnetic domain patterns at different positions (a) Zone 1; (b) Zone 2; (c) Zone 3; (d)-(f) variations of domain pattern of zone 1; (g)–(i) variations of domain pattern of zone 2.

TABLE II. Zones of magnetic domain patterns.

Domain zone segmentation	Location
Zone 1	The central zone
Zone 2	20 ~ 70 μm from the edge
Zone 3	Within 20 μm from the edge

process increases the resistance of magnetic domain movement and thereby increases the hysteresis loss.[8]

In addition, the speed of domain wall movement indicates the speed of magnetization of the sample.[18] Assuming that there is N number of domain walls in the sample, the average core loss per unit volume is expressed as follows:

$$P_v = \frac{1}{w}\frac{1}{t_b - t_a}\sum_{i=1}^{N}\int_{t_a}^{t_b}\alpha_i v_i^2\,dt \tag{2}$$

where w is the sample width, t_a and t_b are the corresponding time when the magnetic domain wall locates at positions a and b, respectively. v_i and α_i are the moving speed and damping coefficient of the magnetic domain wall, respectively.

It can be seen in Fig. 5 that the domain width increases from 0.8 ~ 1 μm in the central zone of the rope-like domain to 2 ~ 4 μm at the edge, and the domain width is the distance of the domain wall movement. Based on the distance of the magnetic domain wall movement and the time of the applied magnetic field, it can be calculated that the average movement rate of the magnetic domain wall increases from 0.11·~ 0.13 μm/s to 0.55 ~ 1.1 μm/s. A significant increase in the rate of motion of the magnetic domain walls at the edges can be observed, resulting in a significant increase in the core loss of the sample.

IV. CONCLUSION

The effect of laser cutting on non-oriented electrical steel 35WW250 was investigated based on the microstructure and magnetic properties measurement and analysis. The laser cutting process leads to the degradation of the magnetic properties of the non-oriented steels, in which the transverse depth of deterioration

© Author(s) 2023

reaches up to 18 mm from the cut edge. Compared with the central zone, the loss at the edge of the sample increases by 13.5%. The increase in frequency intensifies the edge effect, leading to an increase in the total losses. The internal stress introduced by laser cutting leads to a significant variation of the magnetic domain pattern at the edge, which increases the resistance to domain movement and leads to increasing losses in the non-oriented steel. This research can provide a guide for modeling and calculation of magnetic properties of non-oriented electrical steels used in electrical machines under working conditions.

ACKNOWLEDGMENTS

This work was supported in part by the National Natural Science Foundation of China, (No. 52277008, 92066206, 52130710), and the Funds for Creative Research Groups of Hebei Province, (No. E2020202142).

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Changgeng Zhang: Conceptualization (lead); Methodology (equal); Writing – review & editing (equal). **Yan Zhang**: Investigation (equal); Writing – original draft (equal). **Yongjian Li**: Methodology (supporting). **Qingxin Yang**: Methodology (supporting).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] A. Daem, P. Sergeant, L. Dupré *et al.*, "Modeling interlocking effects on core losses in electrical steel," IEEE Transactions on Electrical and Electronic Engineering **15**(12), 1836–1843 (2020).

[2] A. Daem, P. Sergeant, L. Dupré *et al.*, "Magnetic properties of electric steel after plastic deformation," Materials **13**(19), 4361 (2020).

[3] H. Naumoski, B. Riedmüller, A. Minkow *et al.*, "Investigation of the influence of different cutting procedures on the global and local magnetic properties of non-oriented electrical steel," J. Magn. Magn. Mater. **392**, 126–133 (2015).

[4] G. Loisos and A. J. Moses, "Effect of mechanical and Nd: YAG laser cutting on magnetic flux distribution near the cut edge of non-oriented steels," Journal of Materials Processing Technology **161**(1–2), 151–155 (2005).

[5] A. Saleem, N. Alatawneh, R. R. Chromik *et al.*, "Effect of shear cutting on microstructure and magnetic properties of non-oriented electrical steel," IEEE Trans. Magn. **52**(5), 2001904, 2016.

[6] E. G. Araujo, J. Schneider, K. Verbeken *et al.*, "Dimensional effects on magnetic properties of Fe–Si steels due to laser and mechanical cutting," IEEE Trans. Magn. **46**(2), 213–216 (2010).

[7] Y. Li, Y. Fu, Y. Dou, C. Zhang, and K. Zhang, "Magnetic properties measurement and analysis of electrical steel sheet under cutting influence," AIP Advances **11**(2), 025115 (2021).

[8] A. Saleem, N. Alatawneh, T. Rahman *et al.*, "Effects of laser cutting on microstructure and magnetic properties of non-orientation electrical steel laminations," IEEE Trans. Magn. **56**(12), 6100609 (2020).

[9] M. Hofmann, H. Naumoski, U. Herr, and H.-G. Herzog, "Magnetic properties of electrical steel sheets in respect of cutting: Micromagnetic analysis and macromagnetic modeling," IEEE Trans. Magn. **52**(2), 2000114 (2016).

[10] K. Bourchas, A. Stening, J. Soulard *et al.*, "Quantifying effects of cutting and welding on magnetic properties of electrical steels," IEEE Trans. Ind. Appl. **53**(5), 4269–4278 (2017).

[11] M. Bali and A. Muetze, "Influences of CO_2 laser, FKL laser, and mechanical cutting on the magnetic properties of electrical steel sheets," IEEE Trans. Ind. Appl. **51**(6), 4446–4454 (2015).

[12] V. I. Pudov and Y. N. Dragoshanskii, "Domain structure and magnetic losses in laminated magnetic circuits upon laser treatment," The Physics of Metals and Metallography **116**(6), 538–543 (2015).

[13] G. Bertotti and G. Proper, "General properties of power losses in soft ferromagnetic materials," IEEE Trans. Magn. **24**(1), 621–630 (1988).

[14] F. Qiu, M. J. Klug, G. Tian *et al.*, "Influence of magnetic domain wall orientation on Barkhausen Noise and magneto-mechanical behavior in electrical steel," J. Phys. D: Appl. Phys. **52**(26), 265001 (2019).

[15] M. Bali, H. De Gersem, and A. Muetze, "Determination of original non-degraded and fully degraded magnetic characteristics of material subjected to laser cutting," IEEE Trans. Ind. Appl. **53**(5), 4242 (2017), properties of power losses in soft ferromagnetic materials," IEEE Trans. Magn. 24(1), 621–630 (1988).

[16] S. E. Zirka, Y. I. Moroz, S. Steentjes *et al.*, "Dynamic magnetization models for soft ferromagnetic materials with coarse and fine domain structures," J. Magn. Magn. Mater. **394**, 229–236 (2015).

[17] V. Manescu, G. Paltanea, E. Ferrara *et al.*, "Influence of mechanical and water-jet cutting on the dynamic magnetic properties of NO Fe-Si steels," J. Magn. Magn. Mater. **499**, 166257 (2020).

[18] G. Bertotti, *Hysteresis in Magnetism* (Elsevier Academic Press, 1998).

© Author(s) 2023