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# Experimental impact of pulsed laser irradiation, scribing and ablation on 2-D scalar and vector magnetic losses and general properties of Grain-Oriented Electrical Steels

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Increasing the efficiency of electrical equipment and machines (transformers, large alternators) is a global aim and a way to contribute to its fulfilment is to reduce iron losses of soft magnetic materials within their magnetic cores. Improvement of soft magnetic material properties, especially Grain-Oriented Electrical Steels (GOES), is possible using surface laser treatments and is classically obtained for alternating fields parallel to the Rolling Direction (RD). However, flux lines are not always parallel to this preferred direction and can also rotate. The behavior of laser treated GOES under rotational and alternating fields parallel to the Transverse Direction (TD) remains slightly explored and can be investigated further. In this paper, the magnetic behavior of GOES samples is measured with both unidirectional (with Single Sheet Tester (SST)) and rotational (with Rotational power loss Single Sheet Tester (RSST)) fields. Then, the experimental impacts of different laser treatments (irradiation, scribing and new laser process called ablation with Ultra-Short laser Pulses) on 1-D, 2-D and rotational magnetic losses are compared and discussed. The goal is to optimize the vector behavior of GOES. Power loss reductions are reported for several laser sets of parameters and for several polarization/frequency conditions under both unidirectional and rotational fields. Finally, a short analysis on the difference between rotational and average alternating losses leads to use 2-D vector magnetic properties involving a RD-TD coupled loss contribution while characterizing soft magnetic materials.

Index Terms—2-D Scalar and Vector Magnetic Properties, Grain Oriented Electrical Steels, Iron losses, Laser treatment

## I. INTRODUCTION

IRON losses can be reduced using surface laser treatments through the magnetic domain refinement technic [1]-[2]. These improvements are obtained for unidirectional excitation fields parallel to the Rolling Direction (RD) of Grain-Oriented Electrical Steels (GOES). However, in rotating electrical machine applications, the flux is bi-directional and/or rotational in some parts of the magnetic circuit (mainly within the yoke). In addition, alternating losses (occurring in the teeth) are due to flux variations in directions which are not always parallel to the preferred RD. Measurements under rotational fields are still not part of classical characterizations. Still, authors investigate the rotational behavior [3]-[4], its connection to unidirectional components and the dependence on the angle between applied field and the RD [5]. Meanwhile, few started to investigate the impact of an irradiation laser process on the rotational magnetic behavior of GOES [6] but recent advancement in laser technologies revealed new possibilities for beneficial laser treatments [7] that have not been investigated under rotational fields yet. The present paper includes an experimental study of three laser process configurations that are investigated and compared in terms of impacts on the power losses of GOES for both unidirectional (in RD, but also in the Transverse Direction (TD)) and rotational excitation fields. Focus is made on new process called ablation (engraving obtained with Ultra-Short-Pulse (USP) laser technology) for which up to 4 laser parameters are compared.

The goal is to optimize the behavior of GOES in both unidirectional and rotational fields for electrical machines. Finally, the comparison of the different laser impacts emphasizes the difference between unidirectional and rotational magnetization processes and the necessity to use an adapted 2-D vector model to represent power losses and fully understand and optimize the impact of the laser.

## II. EXPERIMENTS

### A. Equipment and accuracy

Magnetic properties measurements have been carried out with two different apparatuses: a Single Sheet Tester (SST150) and a Rotational power loss Single Sheet Tester (RSST60). Magnetic observations were performed (for all samples, at each step, in the same location) using a Magneto-Optical Indicator Film technic (MOIF). Concerning the SST, an accuracy study was carried out by the authors (measurement of the same sample several times with (repeatability) or without (accuracy) complete removal). Measurement error varies with polarization and frequency but is always under 5%: about 5% error for low frequency (5 Hz) and low polarization (0.1 T), about 1% error for high polarizations (> 1 T) and frequencies (> 150Hz). Same error orders are considered for the RSST. Error bars are not plotted on upcoming figures for better legibility.

### B. Material

The considered material is a laboratory Fe-3%Si GO grade from APERAM© company. It is 0.27 mm thick, isolated thanks

to a CARLITE® coating of 3-4  $\mu\text{m}$  thickness and the mass density equals  $7650 \text{ kg.m}^{-3}$ . The samples size depends on the equipment:  $150\text{mm}\times 150\text{mm}$  with the SST and  $60\text{mm}\times 60\text{mm}$  with the RSST. As to avoid any sample dispersion, measurements are systematically carried out at each step (before/after laser treatment) on the same sample, with no significant mass variation (less than 0.1%) even for the ablation process. Remaining errors are caused by the apparatus precision and the repeatability of the measurement (see section II.A.).

### C. Laser treatments

The samples have been laser treated with a pattern composed of distant parallel lines perpendicular to RD. The laser treatments were classified into three categories fully described in [7]: Irradiation (Irr., thermal effect), Scribing (Scrib., thermal effect and weak engravement due to melting), and Ablation (Abl., predominant engravement due to sublimation). All laser treatments were performed with the same fixed spot size. Two different lasers have been used: an IPG pulsed Ytterbium fiber laser with  $1.064 \mu\text{m}$  wavelength (for Irr. and Scrib.) and a USP laser of  $1.030 \mu\text{m}$  wavelength (for Abl.). Laser configurations are given in Table I. The four ablation configurations differ in terms of Cumulative Energy Density (CED) (Abl.1 & Abl.3), peak power (Abl.1 & Abl.2) or pattern (Abl.1 & Abl.4). The CED can be deduced from the laser power at focal point and is related to the process parameters (frequency, speed, number of pass, etc.). The peak power of laser pulse is very high in the case of ablation due to the use of USP femtosecond laser.

### D. Data processing and nomenclature

Measurements have been carried out twice per sample at each step: with the excitation field parallel to RD and parallel to TD when using the SST, in ClockWise (CW) and Counter-ClockWise directions (CCW) when using the RSST. RSST measurements were performed at fixed circular polarization and axis ratio has been kept as close as 1 as possible. Power losses are classically estimated by the measurements (see (1) and (2)). They will be noted  $P_{N,M}$  ( $\text{W.kg}^{-1}$ ) with  $N$  corresponding to the field configuration (i.e. RD, TD, CW, CCW) and  $M$  corresponding to the considered step (i.e. B for Before or A for After laser treatment).  $P_{RD,B}$ ,  $P_{RD,A}$ ,  $P_{TD,B}$  or  $P_{TD,A}$ , represented by  $P_U$ , can be retrieved using (1), with  $H$  the applied magnetic field ( $\text{A.m}^{-1}$ ) and  $B$  the average magnetic induction (T).

$$P_U = \frac{f}{d_m} \int_0^T \left( H(t) \cdot \frac{dB(t)}{dt} \right) dt \quad (\text{W.kg}^{-1}) \quad (1)$$

TABLE I

LASER CONFIGURATIONS (SAME PATTERN FOR ALL EXCEPT ABL.4)

Laser treatment / Designation		CED [ $\text{J/cm}^2$ ]	Peak power [kW]
Irradiation	Irr.	509	0.25
Scribing	Scrib.	611	3
Ablation 1	Abl.1	1171	$460.10^3$
Ablation 2	Abl.2	1426	$560.10^3$
Ablation 3	Abl.3	2343	$460.10^3$
Ablation 4	Abl.4	1171	$460.10^3$

$P_{CW,B}$ ,  $P_{CW,A}$ ,  $P_{CCW,B}$  or  $P_{CCW,A}$ , represented by  $P_R$ , can be retrieved using (2), with  $H_x$ ,  $H_y$ ,  $B_x$ , and  $B_y$  the orthogonal components of applied excitation field ( $H_x$ ,  $H_y$ ) ( $\text{A.m}^{-1}$ ) and of the average magnetic induction ( $B_x$ ,  $B_y$ ) (T).

$$P_R = \frac{f}{d_m} \int_0^T \left( H_x(t) \cdot \frac{dB_x(t)}{dt} + H_y(t) \cdot \frac{dB_y(t)}{dt} \right) dt \quad (\text{W.kg}^{-1}) \quad (2)$$

In (1) and (2),  $f$  represents the considered frequency (Hz),  $T$  equals  $1/f$  (s) and  $d_m$  is the mass density ( $\text{kg.m}^{-3}$ ).  $N$  can also take the following values: ROT (ROTational losses obtained by averaging CW and CCW power losses), ALT\_AVG (AVerAge ALTernating losses obtained by averaging RD and TD power losses) and ALT\_SUM (SUM of ALTernating RD and TD power losses). Measurements have been performed for several polarization and frequency conditions.

## III. RESULTS AND DISCUSSION

Fig. 1, Fig. 2, and Fig. 4 to Fig. 8 show the power loss variations after laser treatment  $\Delta P_N$  calculated using (3). The y-axis scale is fixed to ease comparisons between those figures. If  $\Delta P_N$  is negative, laser process allowed power loss reduction.

$$\Delta P_N = \left( \frac{P_{N,A} - P_{N,B}}{P_{N,B}} \right) \cdot 100 \quad (\%) \quad (3)$$

### A. Unidirectional fields (parallel to RD or TD)

Fig. 1 and Fig. 2 show the evolution of power loss variation after laser treatment with polarization for several laser configurations with the excitation field parallel to RD (Fig. 1) and to TD (Fig. 2) at 50 Hz frequency.

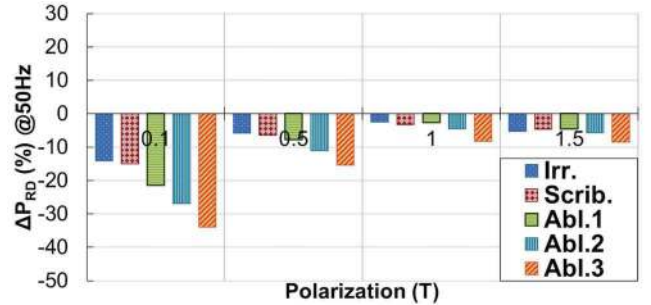


Fig. 1. Power loss variation after laser treatment ( $\Delta P_{RD}$ ) for several laser configurations under excitation field parallel to RD at 50 Hz.

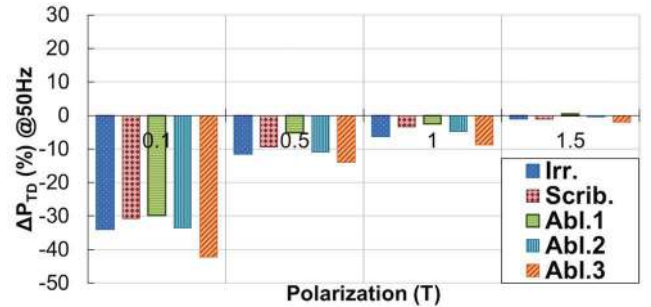


Fig. 2. Power loss variation after laser treatment ( $\Delta P_{TD}$ ) for several laser configurations under excitation field parallel to TD at 50 Hz.

It is shown that it is possible to reduce the power losses in both RD and TD, and sometimes even more in TD than in RD, especially for irradiation and scribing processes and for low polarizations. For example, for Irr., the reduction rate in TD is nearly twice the one obtained in RD at 0.5 T / 50 Hz. The ratio between power loss variations  $\Delta P_{TD}/\Delta P_{RD}$  decreases as the polarization level increases. It can be shown in the MOIF observations of Fig. 3 that long  $180^\circ$  magnetic domains along RD are separated into shorter ones by the laser lines parallel to TD. The physical impacts of the different laser processes on the magnetic structure have already been discussed in [7] considering fields parallel to RD. Depending on the process, the “new” domains configuration might involve more mobile walls, additional misoriented and/or closure domains, higher demagnetizing energy, etc. At low polarization and medium frequency (from 5 Hz to 500 Hz): the increase of walls density and mobility can explain the power loss reduction in RD. In TD, the spontaneous generation of misoriented and/or closure domains at the vicinity of the laser spots, that induce some stress and/or magnetic poles even at rest, can contribute to reduce the power loss. At low polarization, potentially stress-induced misoriented and  $90^\circ$  closure domains might ease the transverse magnetization by delaying and slightly lessening the domain rotation phase which is more energy consuming than the walls displacement mechanism. At high polarization, the material saturates. Thus, previously exposed domain structure specificities in comparison with the directions are no longer predominant as the wall density is decreased. As a result, effects of the laser tend to be the same for both RD and TD at higher polarizations.

Returning to Fig. 1 and Fig. 2, the tendency is globally the same for RD and TD configurations: the lower the polarization, the most beneficial the impact of the laser (at fundamental frequencies from 5 Hz to 500 Hz and especially at 50 Hz). Then, time harmonic losses with low magnitude may also be reduced with an appropriated laser treatment. Fig. 4 and Fig. 5 show the evolution of power loss variations after laser treatment with frequency for several laser configurations with the excitation field parallel to RD (Fig. 4) and to TD (Fig. 5) at 0.1 T.

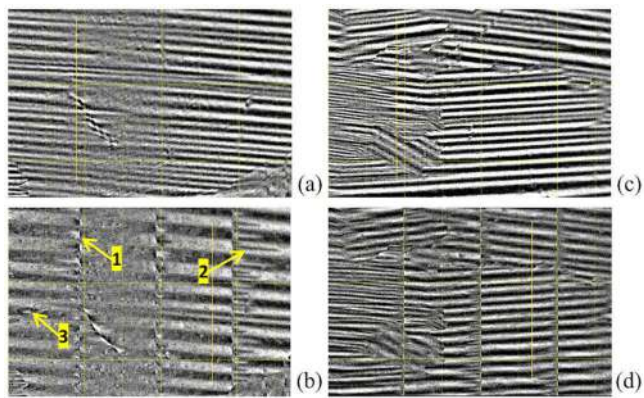


Fig. 3. MOIF observations: before (a) and after (b) Irr. (1: misoriented and/or  $90^\circ$  closure domain, 2 spike-like domain, 3: Lancet domain); before (c) and after (d) Abl.2 (12.42mm $\times$ 18.56mm images, center of 60mm $\times$ 60mm samples).

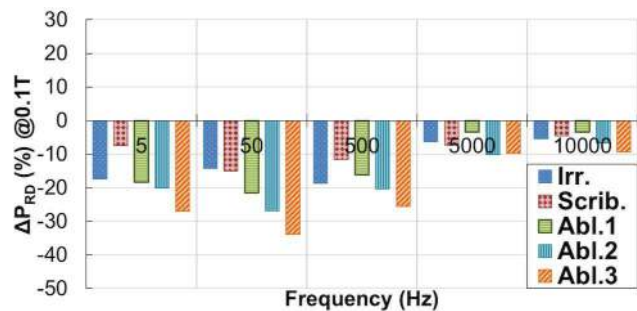


Fig. 4. Power loss variation after laser treatment ( $\Delta P_{RD}$ ) for several laser configurations under excitation field parallel to RD at 0.1 T.

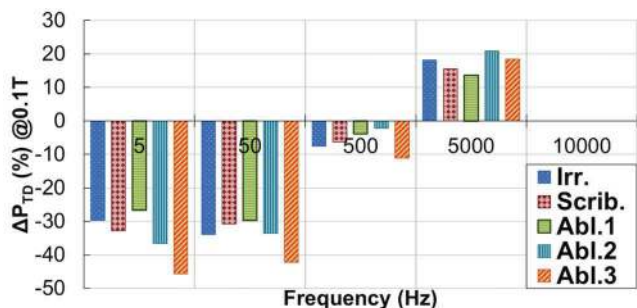


Fig. 5. Power loss variation after laser treatment ( $\Delta P_{TD}$ ) for several laser configurations under excitation field parallel to TD at 0.1 T.

The reduction rates are in the same range from 5 Hz to 500 Hz in RD configuration (always better than -11.5% (Scrib.)). Similar behavior is observed in [7] under close experimental conditions for several laser processes especially at low induction. On the contrary, in TD, better reduction rates are obtained for low (5 Hz) and medium (50 Hz) frequencies, but laser treatment can worsen the power loss when the frequency increases whereas polarization is kept constant at 0.1 T (for example: -10% power loss variation in RD against +21% in TD for Abl.2 laser configuration at 5 kHz). A laser treatment has a different effect depending on the frequency according to the field direction. From Fig. 4 and Fig. 5, it is clear that laser processes have a beneficial impact on both hysteresis and excess iron losses at low and medium frequencies (from 5 Hz to 500 Hz) in both RD and TD directions. Classical eddy current losses shall not be significantly changed by the laser (constant thickness) [8]. However, at higher frequencies (up to more than 5 kHz), the domains refinement in RD shown in Fig. 3 will still be responsible for an excess loss reduction in RD but can increase the TD losses at the same time. While the  $180^\circ$  walls are multiplying,  $90^\circ$  walls density and/or mobility may be reduced. This detrimental aspect must be taken into account when using laser processes in magnetic cores.

The behavior of laser treated GOES under unidirectional fields (RD and TD) was exposed through previous graphs. To ease comparisons with rotational behavior, RD and TD contributions have been lumped in average contributions  $P_{ALT\_AVG,B}$  and  $P_{ALT\_AVG,A}$  that have been compared resulting in average loss variation ( $\Delta P_{ALT\_AVG}$ , see Fig. 8).

## B. Rotational fields

Whereas all laser treatments were beneficial in both RD and TD at 50 Hz, some are detrimental when the field rotates (see Fig. 6 and Fig. 8). Indeed, there is a clear difference of behavior for ablation laser treated samples notably at 50 Hz whereas for Irr., which allows comparable reduction rates to the ones obtained in [6] under similar experimental conditions, alternating and rotating behaviors are very close. In [7], it is mentioned that, in the case of irradiation, Lancet (zone n°3 in Fig. 3b), spike-like (zone n°2 in Fig. 3b), and 90° closure domains (zone n°1 in Fig. 3b) may be created in numbers and at a very small scale compared to other processes. Those closure domains could be beneficial for the material submitted to a rotating field, especially not in the rolling direction. Those misoriented domains are scarcer for Abl.2 process near the laser lines (see Fig. 3d). Ablation is usually used to mainly engrave the material without thermal stress effect, but it might have a pronounced purely mechanical impact inside the thickness at a certain depth (resulting in misoriented domains under the laser spots).

Then, concerning the study at fixed polarization (see Fig. 7), as for TD configuration, the higher the frequency, the less beneficial the impact of the laser (losses can even be worsened for some conditions). Laser treatments seem to reduce both hysteresis and excess iron losses but only at low and medium frequencies (from 5 Hz to 500 Hz). As aforementioned, at higher frequencies, the usual excess losses can still be reduced but only in RD. A detrimental effect occurs in TD and under rotational excitation which is probably due to an unknown and unusual excess loss term induced by the misoriented walls displacement.

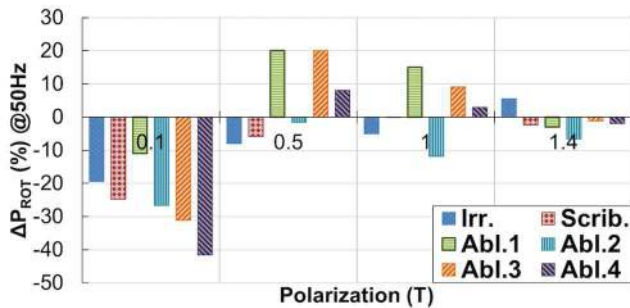


Fig. 6. Power loss variation after laser treatment ( $\Delta P_{ROT}$ ) for several laser configurations under rotational excitation field at 50 Hz.

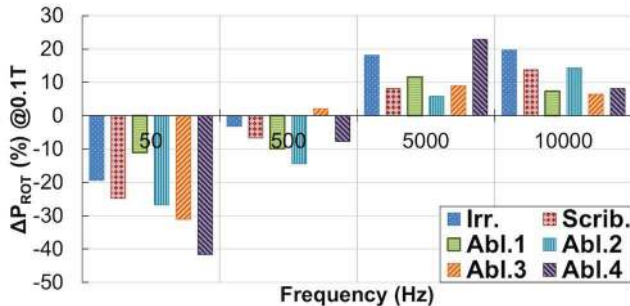


Fig. 7. Power loss variation after laser treatment ( $\Delta P_{ROT}$ ) for several laser configurations under rotational excitation field at 0.1 T.

Rotational magnetization is very specific and involves not only the walls motion mainly but also the domains magnetization rotation. As exposed in section IV., mechanisms at stake should be better understood through the development of an adapted vector model.

## C. Optimization of laser parameters

It results from both macroscopic and microscopic observations that the impact on power losses depends on the laser process. For Irr. and Scrib., both alternating and rotating losses behaves similarly. Concerning Abl., several laser configurations were tested as a first attempt of optimization (see Fig. 8). In the case of unidirectional fields, Abl.3 was more beneficial than Abl.2, itself more beneficial than Abl.1. Then, by comparing both alternating and rotational behaviors, and in relation with laser parameters exposed in Table I, one seems to tend towards an optimum being Abl.2: it has similar or better impact than Irr. in RD and TD, and it happens to be better under rotational fields. For the considered grade, for a fixed pattern, using an intermediate and optimized CED (between low (Abl.1) and high CED (Abl.3)) in parallel with a sufficiently high peak power (USP) seems beneficial.

## IV. PERSPECTIVES

Finally, alternating and rotating power losses are compared in Fig. 8. In most cases here:  $P_{ALT\_AVG} < P_{ROT} < P_{ALT\_SUM}$ . This representation could also be expressed as in (4) depending on the contributions at stake with  $P_{CPGi}$  ( $W \cdot kg^{-1}$ ), a CouPlinG term between rotational and alternating contributions.

$$\begin{cases} P_{ROT,M} = P_{ALT\_AVG,M} + P_{CPG1,M} \\ P_{ROT,M} = P_{ALT\_SUM,M} - P_{CPG2,M} \end{cases} \quad (4)$$

$P_{CPGi}$  might be related to the non-diagonal terms in 2-D vector magnetic properties such as in [9]. To highlight this, the evolution of the relative difference  $\Delta P_{CPG1}$  (defined in (5)) versus polarization at 50 Hz is shown in Fig. 9.

$$\Delta P_{CPG1} = \left( \frac{\Delta P_{CPG1,A} - \Delta P_{CPG1,B}}{\Delta P_{CPG1,B}} \right) \cdot 100 (\%) \quad (5)$$

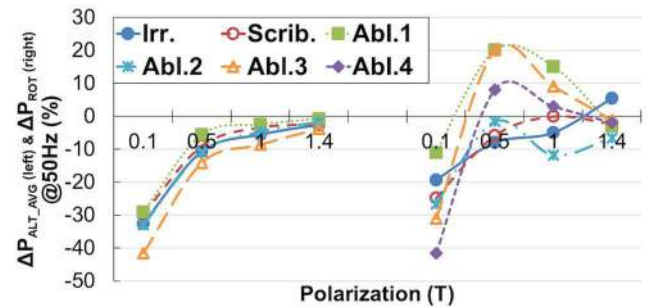


Fig. 8. Average alternating ( $\Delta P_{ALT\_AVG}$ , left) and rotational ( $\Delta P_{ROT}$ , other view, right) power loss variations after laser treatment at 50 Hz.

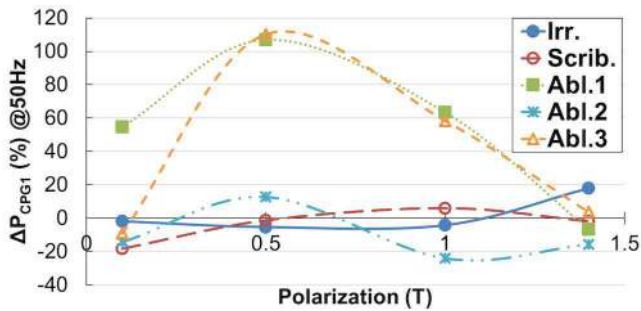


Fig. 9. Relative difference  $\Delta P_{CPGI}$  between coupling terms (between rotational and average alternating power losses) at 50 Hz.

Fig. 9. shows that a high absolute value of  $\Delta P_{CPGI}$  implies strong differences of impacts on power losses whether the field is rotational or unidirectional. The tendency observed in Fig. 8 (right part) also emerges in Fig. 9. The variations of  $P_{CPGI}$  loss part contributes to the total losses but can be analyzed separately in order to understand excess losses due to field rotations. For example, Abl.1 and Abl.3 were beneficial in RD and TD but detrimental under rotational field for medium polarizations, Abl.2 allowed reductions under both alternating (-5% in average) and rotating field (-12%) at 1 T / 50 Hz but in different ranges (see Fig. 8). Having  $\Delta P_{CPGI} \approx 0$ , means having the same impact on rotational and unidirectional losses. The next goal for the authors is to understand how to link this excess coupling term due to field rotations with the laser impact.

## V. CONCLUSION

To conclude, outcomes of this paper may be summarized as follows. Several types of laser treatments including irradiation, scribing and ablation processes can be beneficial regarding power loss reduction in RD, TD but also under rotating field. However, laser treatment may be beneficial in RD and TD but not under rotational field unless it is optimized. After optimization, ablation process may be as interesting as classical irradiation process for reducing power losses, especially regarding rotational behavior. Finally, it is necessary to study vector 2-D magnetic properties to correctly characterize soft magnetic material in general, and more specifically when investigating the impact of laser treatments. In further work, the authors should investigate deeper the impacts of laser on 2-D vector magnetic properties, and especially on the coupling terms existing between RD and TD contributions.

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