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GOES's Domain Structure in the Vicinity and On the Lines Post-Laser Treatment

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Pulsed laser processing for domain's refinement is a recent technology implemented on an industrial scale. The present study focuses on the impact of different laser pulse durations on the magnetic properties such as total losses and domain structure of 0.28 mm thick grain-oriented electrical steel (GOES). Three pulse durations are considered Long Pulse (LP), Short-Pulse (SP) and Ultra-Short Pulse (USP). The latter has not been yet applied for domain refinement treatments, hence the interest of this research. Iron loss measurements made with the single sheet tester (SST) demonstrated a maximum loss reduction of 18% at induction of 0.5T and a frequency of 50Hz following USP laser treatment. At a high induction of 1.7T and a frequency of 50Hz, both LP and USP pulse lengths achieved a reduction in total losses of 16%. Moreover, the behaviour of the magnetic structure under laser treatment was detailed. The magnetic images were visualized by magneto-optical indicator film (MOIF). A reduction from 308 μm to 217 μm in the average domain size was observed post laser treatment with USP duration. Furthermore, the domain structure in the vicinity and on the laser line was visualized on a nanoscale using a magnetic force microscope (MFM). All these results confirmed the dependence of the laser-matter interaction on the laser pulse duration.

Keywords—Domain structure, Electrical steels, Pulsed laser, Surface treatment, Power loss, MFM, MOIF

1. Introduction

Magnetic domain refinement is a technique widely used by manufacturers of grain-oriented silicon steels to reduce iron losses (1). The impact of domain refinement using advanced pulsed lasers on the power loss of grain-oriented FeSi steels has been investigated (2) (3), with apparently some specificities depending on the pulse duration. Puchy et al. studied surface treatment using a pulsed fibre laser with a wavelength of 1064 nm and pulse duration between 50 μs and 500 μs on Fe-3.2Si electrical GOES(M165-35S). They proved a decrease in magnetic domain width for high laser pulses number with an optimum of 10 pulses for single pulse energy of 0.6 mJ (4). The physical origins of the changes in domain's structure due to laser treatment are not fully detailed yet. Thus, these origins may help to better explain the impact of laser processing on the macro-scale magnetic properties. Surface treatment with an ultra-short pulse laser (USP) remains unfamiliar for the refining of electrical steels, although it presents a great potential, mainly as a reproducible and high temperature resistant process. In this work, we studied the behaviour of iron loss and domain structure of grain oriented electrical steel (GOES) submitted to laser treatment with different pulse widths, with emphasis on the effect of ultra-short pulses.

We distinguished three types of laser effects depending on the pulse duration (thermal effect, groove effect or both). The laser treatment with LP duration had mainly a thermal effect while the short pulse duration presented a thermal effect that led to slight grooves on the material's surface. Lastly, the ultra-short pulse duration showed clean grooves of some micrometres in depth (5). Regarding the experimental measurements, power losses were identified with single sheet tester equipment (SST - BROCKHAUS Measurements) ensuring an accuracy of 0.5% at high induction and 3% at low

induction. The magnetic domain width was visualized with a magneto-optical indicator film (MOIF). Finally, a complete understanding of the magnetic domain structure on laser spot and in the vicinity of the laser line was detailed using a Magnetic Force Microscope (MFM).

2. Experimental Procedures

2.1. Material and laser treatment

The considered material is a commercial grain-oriented Fe-(3wt%)Si [R120-27] with a thickness of 0.28 mm. A pulsed Ytterbium fiber laser with a wavelength of 1.064 μm and pulse duration between 4 ns and 200 ns was used to perform treatments with short and long pulse durations. Whereas, an Amplitude laser performing a wavelength of 1.030 μm and a pulse width between a few hundred of fs and 10 ps (see Table 1) was adapted for ultra-short pulse duration treatments. Sheet dimensions were chosen according to the dedicated experimental equipment: 150 mm squared sheets were selected for SST measurements, 60 mm squared sheets for MOIF and 10 mm squared sheets for MFM.

Laser Pulse Duration	Laser Fluence ((J·cm ⁻²))	Peak Power Density (MW·cm ⁻²)
LP	1.27	12.73
SP	0.51	127.32
USP	11.71	23.4 e ⁶

Table 1 Laser fluence and peak power density adjusted with each pulse duration; LP: long pulse duration, SP: short pulse duration, USP: ultra-short pulse duration.

The optical image and profile analysis corresponding to laser effect on the sample surface were presented in a previous article (3): the laser effect was mainly a thermal heating of the surface in the case of LP, without removal of the coating nor significant modification of the surface. For SP laser, the laser line mark sinks a few micrometers into the surface of the sample with formation of relief edges, the coating could be locally damaged

by this process. In the case of USP, this pulse duration permits engraving by sublimation with a laser line mark, the coating and a few μm of metal are thus removed. Therefore, no sheet bending was detected with the optimized laser configurations listed in Table 1.

2.2. Experimental measurements

We visualized the magnetic domain structure of the samples with two different yet complementary magnetic imaging techniques: the magneto-optical indicator film MOIF presented is formed with a thin film of soft magnetic material possessing strong magneto-optical properties (Garnet Film with strong Verdet constant). The imaging concept is as follows: a light beam passes through a polarized layer, and then enters the indicator film placed under the sample. Its polarization will change due to the magneto-optical Faraday Effect between the film's magnetic domains and the magnetic domains of the sample. Thus, the reflected beam's polarization follows the sample's magnetic structure. The magneto-optical image is then recorded by the high-resolution digital camera. The speed and simplicity of visualizing magnetic image are the main advantages of this technique (magnetic image in 1s). However, its resolution is limited to $25\ \mu\text{m}$.

The second imaging technique applied is magnetic force microscopy (MFM). It is an imaging mode of atomic force microscopy (AFM) dedicated to visualize the surface distribution of magnetic domains and walls of the sample. This mode requires a specific probe with a thin layer of magnetic material on the tip. The magnetic images presented in this work were performed with a hard magnetic coating with low magnetic moment on the tip. This imaging mode is based on a two-pass data collection during a scan. In the first pass, the tip scans the surface topography. Then, in the second pass, the tip-sample distance is incremented and held constant based on the topographic line data obtained in the first pass. Thus, the influence of Van Der Waals forces becomes negligible, as the tip is mainly affected by the magnetic force. Thus, the resulting image holds predominantly the magnetic information of the specimen surface. The MOIF imaging tool captures an $18.5 \times 12.4\ \text{mm}$ image and the samples involved were squares of $60\ \text{mm}$ side while smaller samples ($10\ \text{mm}$ square) were used for MFM where the image size is $120 \times 120\ \mu\text{m}^2$. For MFM imaging, chemical and mechanical polishing were performed prior to laser processing on the specimen since high quality MFM imaging requires a smooth surface finish. The polishing procedure started by etching the specimen in a hydrogen chloride solution to remove the insulating coating. Then, the sample was ground with silicon carbide papers of different (successively decreasing) grain sizes. The final polishing step was realized with a colloidal suspension of amorphous silica in order to achieve minimal surface roughness.

Regarding the macroscopic measurements, we measured the total power loss of each sample before and after laser treatment with the SST to ensure an accurate comparison.

3. Experimental results

3.1. Power losses variation

Various laser configurations were tested to finally select the optimal ones resulting in maximum loss reduction. This optimization was performed for each pulse duration (LP, SP and USP) (3) (5). Laser treatments with LP, SP or USP duration were done on three samples. Magnetic measurement was performed for each sample before and after laser treatment by the SST equipment at medium (0.5T and 1T) and high (1.5T and 1.7T) inductions for a frequency of 50 Hz.

In Figure 1, we presented the variation of the total power loss for each sample after treatment measured for the 4 induction levels: 0.5T, 1T, 1.5T and 1.7T at a frequency of 50Hz. The sample exposed to laser treatment at USP duration showed a maximum loss reduction of 18% at an induction level of 0.5T. However, for the induction level of 1.7T, both LP and USP pulse lengths provided 16% reduction in total loss.

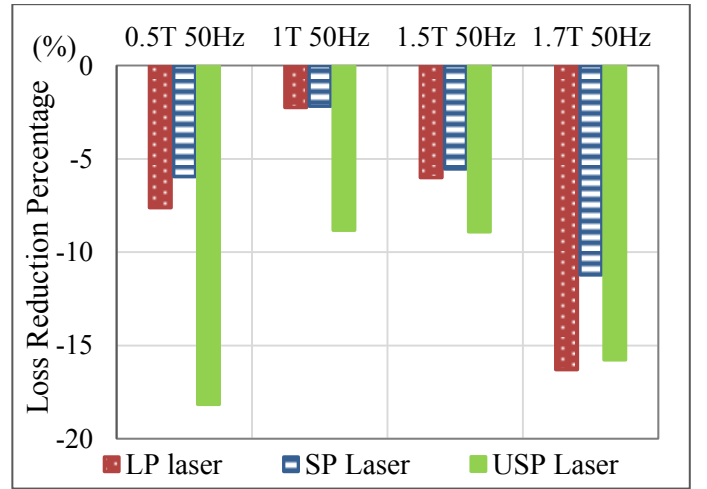


Figure 1 The Percentage of Total Power Losses Variation under Laser Treatment with Different Pulse Durations: Long Pulse (LP), Short Pulse (SP), Ultra-Short Pulse (USP) (sample thickness 0.28mm) (sample thickness 0.28mm) (Measurement accuracy $\pm 1\%$).

3.2. Domains Structures at the Vicinity of Laser Lines (MOIF images)

In parallel, the impact of the laser treatment on the structure of the magnetic domains of the sheet has been investigated. We visualized the change of the magnetic domain structure with MOIF resulting from the laser treatment. Magnetic images were taken in the same area prior and post laser treatment.

Figure 2 illustrates the magnetic domains prior to and post treatment with the LP duration laser. The number of magnetic domains increased across the majority of the sample area. The average domain width reduced from $374\ \mu\text{m}$ to $309\ \mu\text{m}$ (Erreur ! Source du renvoi introuvable.).

Laser Type	Average Domain Width (μm)	
	Initial	After Laser Treatment
LP	374	309
SP	334	326
USP	308	217

Table 2 The Average Width of the Magnetic Domain Before and After the Laser Treatment with Different Pulse Durations.

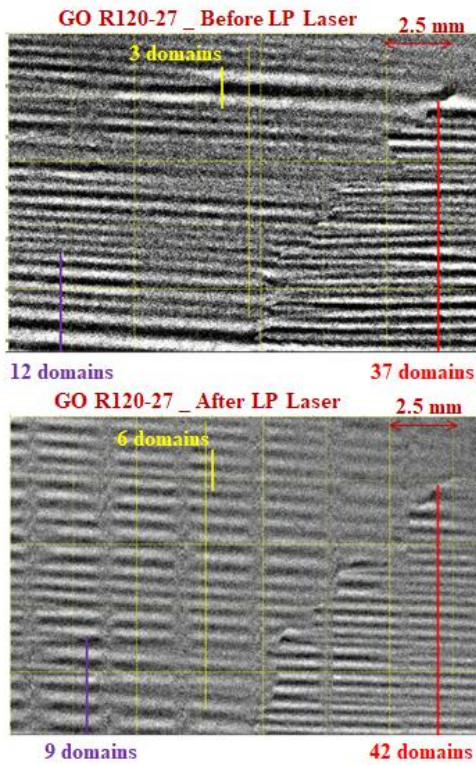


Figure 2 MOIF images of GO Sample ($60 \times 60 \text{ mm}^2$) Before and After Long Pulse (LP) Laser Treatment (image size $12.4 \times 18.5 \text{ mm}^2$) (sample thickness 0.28 mm).

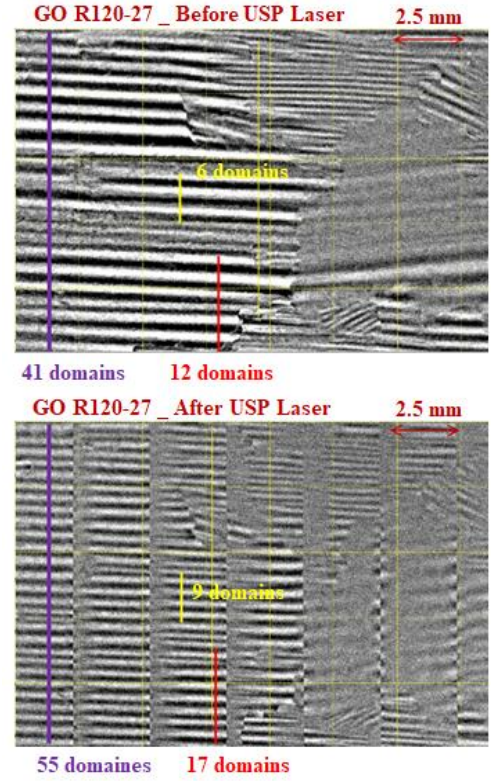


Figure 4 MOIF images of GO Samples ($60 \times 60 \text{ mm}^2$) Before and After Ultra-Short Pulse (USP) Laser Treatment (sample thickness 0.28 mm).

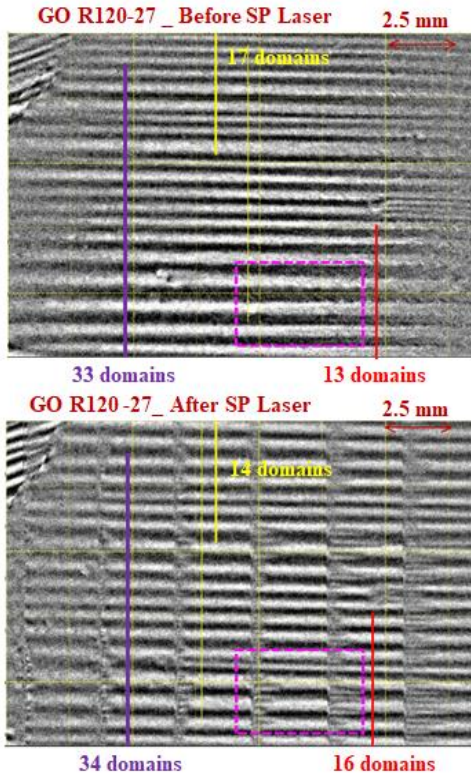


Figure 3 MOIF images of GO Samples Before and After Short Pulse (SP) Laser Treatment (sample thickness 0.28 mm).

3.3. Domains Structures on the Laser Lines (MFM images)

An observation of the magnetic domain structure on the laser lines at a minor scale was performed using MFM (resolution down to a few nanometers). In these images (Figure 5-Figure 7), the dark and light contrasts are representative of the repulsive and attractive interactions between the magnetic layer on the probe and the magnetic domains on the sample surface. These visualizations were performed on 0.23 mm thick Fe-(3wt%)Si, a material of the same grade with lower thickness investigated in our previous publication. This thickness was covered in a previously published paper in which we demonstrated a similar impact of the three laser configurations on the iron loss reduction, even more significant (3) (5). Since these MFM visualizations reveal an interesting magnetic domain behavior according to each pulse duration. We were persuaded of the value to illustrate these results. In Figure 5, laser treatment with LP duration performed a multiplication of relatively small spike-like domains in the vicinity of laser line. According to Néel (6), spike-shaped domains are attached to inclusions and grain boundaries in magnetic materials. These domains tend to facilitate the reversal magnetization mechanisms near the coercive point and the remanence (7) (8). Spike-like domains are relatively thin compared to the main 180° domains observed in MOIF images. The magnetic structure involving these spike-like domains was highly disturbed at a distance from the laser line which refers to the heat affected zone. This zone exhibits significant thermal stress due to the rapid heating and cooling during the laser processing.

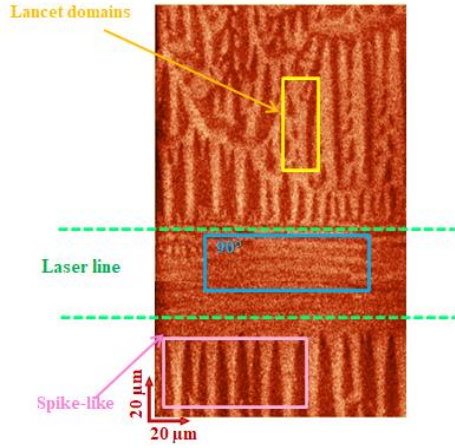


Figure 5 Magnetic Image of GO Sample under a Long Pulse (LP) Laser Treatment Collected with MFM Showing the Magnetic Domain Structure on the Laser Line (sample thickness 0.23mm).

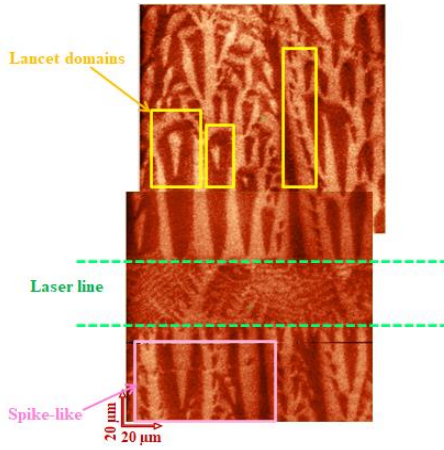


Figure 6 Magnetic Image of GO Sample under a Short Pulse (SP) Laser Treatment Collected with MFM Showing the Magnetic Domain Structure on the Laser Line (sample thickness 0.23mm).

the global domain structure. Both effects are thus compromised, resulting finally in a reduction of the total losses.

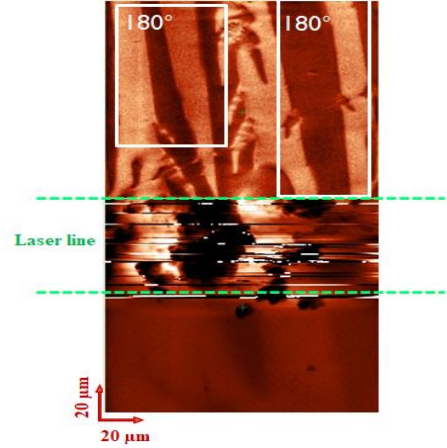


Figure 7 Magnetic Image of GO Sample under a Ultra-Short Pulse (USP) Laser Treatment Collected with MFM Showing the Magnetic Domain Structure on the Laser Line (sample thickness 0.23mm).

When compared to the impacts of LP and SP duration laser treatments, the transient magnetic structure involving the spike-like domains is barely disturbed near the laser path. This could be attributed to laser-matter interaction under the USP laser, which has practically no heat-affected areas. Meanwhile, on the laser path, the plasma formed during the ablation process at extremely high temperature T_e for electrons (9), could generate a surface shock wave at extremely high peak pressure P_r in the axial direction (i.e., perpendicular to the plane of the sheet). The resulting residual stress obtained post treatment contributed to the appearance of domains in different shapes and orientation inside the grooves. Yet, we were not able to capture an image on the laser path as the groove was quit deep to be reached by the tip (groove depth of a few μm). An alternative solution remains to be found to overcome this difficulty and complete the perspective analysis.

4. Conclusions

Each type of laser treatment demonstrated different impact on the power losses and the domain structure. The comparison was noticeable both close to and on the laser path: The long-pulse (LP) and short-pulse (SP) lasers generated thin spike-like domains close to laser path and closure domains (lancet-like domains and 90° plane closure domains) slightly further from these paths. However, the laser with ultra-short pulse (USP) duration generated wider spike-like domains close to the laser path while efficiently minimizing main 180° domains size. It resulted also in less disruption and disorientation in the transition region of the magnetic structure. The distinct impact of each treatment refers to the dissimilar laser-material interactions that took place depending on certain laser parameters, notably the pulse duration. Laser treatment with USP duration laser was proved to be advantageous in reducing the total loss of the 0.28 mm thick FeSi sheets and ensuring a maximum domain refinement.

This probably leads to a residual axial or out-of-plane 1D tensile stress and hence compression in the sample thickness. Lancet closure domains are noticeably clear on the laser path. Laser treatment with SP duration resulted in a similar structure further to the laser path. Relatively small spike-like domains are present near the laser point (Figure 6). This multiplicity of well-oriented closure domains (minimizing magnetic poles and demagnetizing field) improves the magnetization reversal mechanisms under quasi-static working conditions. On the other hand, the magnetic structure involving these spike-like domains remains strongly disturbed even at a certain distance from the laser path (corresponding to the thermally affected area). This area may act as a transition zone between the laser lines with refined closure domains' structure and the nominal 180° main magnetic domains of classical GOES. However, in the case of laser treatment with USP duration, the spike-like domains near the laser line are 180° oriented domains with an average width of $20\ \mu\text{m}$ which is the largest among the other treatments (Figure 7). Although this result is not in favor of the magnetization reversal mechanisms, the laser treatment with USP duration has contributed to an advantageous refinement of

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