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# Core loss reduction in electrical steels through materials processing

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## Abstract

Research has been conducted into the effects of laser scribing on the core losses of soft magnetic materials. Various types of lamination steels for use in electric motors and transformers were studied including iron based alloys containing carbon, silicon, nickel, and cobalt. The results show that the change in core losses for carbon, nickel, and cobalt alloys was small for the scribing conditions examined, but core loss reductions of up to 18% were achieved with iron-silicon alloys.

## Keywords

Carbon, Cobalt, Nickel, Electric motors, Iron

## Disciplines

Electromagnetics and Photonics | Engineering Physics

## Comments

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## Core loss reduction in electrical steels through materials processing

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Research has been conducted into the effects of laser scribing on the core losses of soft magnetic materials. Various types of lamination steels for use in electric motors and transformers were studied including iron based alloys containing carbon, silicon, nickel, and cobalt. The results show that the change in core losses for carbon, nickel, and cobalt alloys was small for the scribing conditions examined, but core loss reductions of up to 18% were achieved with iron–silicon alloys.

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### INTRODUCTION

According to the latest data available the United States consumes  $27 \times 10^{12}$  kWh ( $97 \times 10^{18}$  J or 91 quads) of energy each year. This is equivalent to  $1.9 \times 10^{12}$  \$/yr. About one third of this energy, or  $9.6 \times 10^{12}$  kWh, is consumed by electrical utilities and of this about  $3.5 \times 10^{12}$  kWh is distributed as electrical energy, of which 65%, or  $2.3 \times 10^{12}$  kWh is eventually used by motors. Typical motor efficiencies are 86%, so the losses amount to  $0.32 \times 10^{12}$  kWh annually. These losses consist of electrical heating  $I^2R$  losses and core losses. Research is therefore being carried out into improving core losses in electrical steels for motor applications. An improvement in motor efficiency from 86% to 93% would result in savings of  $35 \times 10^9$  kWh, or  $2.5 \times 10^9$  \$/yr.

### BACKGROUND

Resistive losses comprise the largest part of power losses in motors, but magnetic core losses are also very high. Werner and Jaffee<sup>1</sup> calculated that in 1985 core losses in electric motors amounted to  $45 \times 10^9$  kWh/yr, which is equivalent to about  $3.2 \times 10^9$  \$/yr. By 1997 that figure had risen to  $70 \times 10^9$  kWh/yr or  $4.9 \times 10^9$  \$/yr. There is consequently a need to devise ways to reduce the core losses in lamination steels of which motor cores are constructed. It has been suggested that laser scribing reduces losses in electrical steels.<sup>2,3</sup> This arises because the laser treatment causes localized heating of the material and therefore a shock wave passes through the material leading to localized changes in stress.<sup>4</sup> This alters domain sizes and hence alters anomalous losses associated with the magnetization process in lamination steels.<sup>5</sup> These losses are related to domain wall dynamics and are separate from the well known hysteresis and classical eddy current losses.

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### EXPERIMENTAL METHODS

Experimental work included sample preparation, core loss measurement, and materials processing. The samples were cut to  $10 \times 100$  mm rectangular laminae. These dimensions were used to avoid significant error from the macroscopic demagnetizing field along the long axis.

Core loss was measured on each specimen at 60 and 400 Hz at several induction levels both before and after they were subjected to scribing. The improvement in material properties was determined from the change in core loss. The samples were placed at the center of a solenoid 750 mm in length, wound with 610 turns and driven by a function generator connected to a bipolar power supply. The field in the solenoid was calculated using the solenoid parameters and the current. The latter was measured with a shunt resistor. A search coil of 250 turns was also wrapped around the samples to measure the change in magnetic induction from induced voltage. The shunt voltage and the induced voltage from the search coil were measured using a digital storage oscilloscope. The data was then transferred to a computer running a program developed specifically for this project. This calculated the maximum magnetic induction  $B_{\max}$ , maximum magnetic field  $H_{\max}$ , rms current  $I_{\text{rms}}$ , coercivity  $H_c$ , remanence  $B_r$ , and core loss  $P_{\text{loss}}$  from the raw data. Figure 1 shows a schematic of the configuration of the test setup. The format for the output data was a plot of core loss as a function of magnetic induction  $B$  before and after laser scribing.

The laser used for these tests was a Nd:YAG laser with a wavelength of  $1.06 \mu\text{m}$  with 30 W maximum power. The laser beam was focused to a diameter of  $150 \mu\text{m}$  and the laser power density was typically  $560 \text{ MW/m}^2$ , at an operating current of 30 A. Laser scribing was accomplished by placing the specimen on a computer controlled XY positioning table. The table moved the specimen across the path of the stationary laser beam at a controlled speed. The two parameters used for laser scribing were scanning speed and scribe spacing. The specimens were scribed along the shorter direction which was perpendicular to their rolling direction.

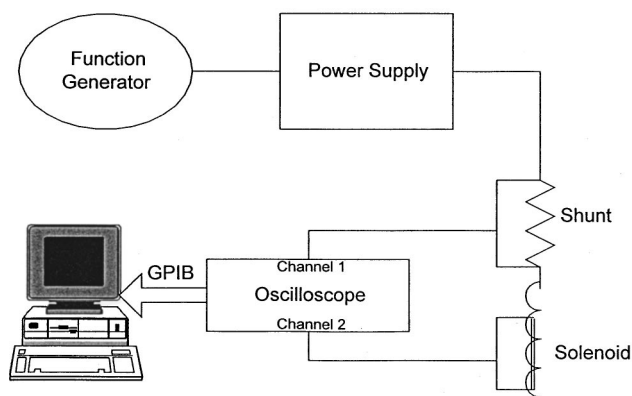


FIG. 1. Core loss measurement system.

In order to determine the change in core loss resulting from laser treatment the same value of induction was used for both curves. This involved interpolating between data points to compare data for the same induction. Typically, the highest induction value for the postlaser scribing data was used with the equivalent induction point from the prelaser scribing data. In most cases the improvements in core loss were observed at the higher magnetic induction amplitudes.

## RESULTS

The present studies on electrical steels have shown that it is possible to reduce core losses by up to 18% of their value in untreated materials by surface treatment. Some of the M-15 and M-19 silicon alloy tests showed a consistent 15%–18% core loss reduction at high induction levels, normally above 1.5 T, at both 60 and 400 Hz. In general, the laser scribing had an effect on the core loss versus induction curve for each material which resulted in a slightly greater core loss at low  $\Delta B$  amplitudes after laser scribing but a smaller core loss at high  $\Delta B$  amplitudes. The laser scribing conditions, power density, scribing velocity, and spacing had significant effects on the core loss, so that careful control of the scribing parameters was necessary to get optimal reductions in core losses.

A summary of the results on all of the samples is included in Table I. This shows the sample identification, laser scribe spacing, scribe table velocity, laser current, and the maximum change in core loss from the prelaser to postlaser scribed. Positive numbers correspond to a decrease in core loss while negative numbers refer to an increase in the core loss.

### IRON-CARBON ALLOYS

A 3.6% improvement in core losses was observed for 0.6 mm thick CQ carbon steel at 60 Hz, although the “before” and “after” curves appeared to be very close and the small difference probably fell within experimental uncertainty. Additionally, this small amount of improvement occurred with greater exposure to laser scribing. The slow scanning speed and small scribe increment corresponds to the largest amount of laser exposure for any sample. The 0.6 mm Magnetek MS 1470 sample showed about 6% core loss improvement at 60

Hz, although it too was subjected to greater exposure to laser treatment. The improvement was slightly smaller for 400 Hz.

### IRON-COBALT ALLOYS

The 0.15 mm Hiperco 50 alloy was annealed at 800 °C for 50 min in order to perform a stress relief anneal. The cobalt samples seemed more sensitive to error in core loss measurement which could be due to the shape of their core loss versus induction curve. The samples showed only slight sensitivity to the scribing parameters. The 0.35 mm Hiperco 50 alloy was also annealed at 800 °C for 50 min. The results from these samples are difficult to determine due to the shape of their core loss versus induction curve. Results showed up to 14% core loss improvement for the sample, although the general applicability of this result is open to doubt since the same scribing parameters were used for another sample with only small improvement at 400 Hz. In general, the sensitivity of cobalt alloys to laser scribing seemed to vary significantly.

### IRON-NICKEL ALLOYS

The nickel alloys also had a very sharp upward curve in core loss versus  $\Delta B$  amplitude which made quantification of core loss improvement very difficult. From the data however it was clear that none of the laser scribing conditions resulted in a reduction in core loss. Seven different scribing configurations were attempted with no success. Either the scribing conditions chosen were far from the range that could provide improvement, or core loss reduction through laser modification of domain boundaries is difficult to realize in these alloys.

### IRON-SILICON ALLOYS

In general, less laser exposure was required for thinner gauge materials. The 0.13 mm Magnesil sample was the thinnest sample of all of those studied in this research and the only one in which the laser power density needed to be reduced in order to achieve positive results. All of the silicon samples showed some mechanical deformation as a result of laser scribing which resulted in a slight curling of the sample. The thinnest sample was severely deformed by the laser, and in this case the results proved that too much laser exposure of a thin sample can actually increase the core loss. Other samples only showed core loss improvement at the 400 Hz test frequency.

The 0.45 mm M-36 silicon steel sample showed improvements in core loss for all laser parameters tested. Some of the core loss versus magnetic induction amplitude curves were not very smooth, so that exact determination of the improvement was difficult. However, the general trend of the data was such that there was an improvement at the highest inductions tested for both 60 and 400 Hz. The test data exhibited fluctuations, but the general trend was that there was more improvement in core losses at higher inductions.

TABLE I. (a) and (b) Changes in core loss at 60 and 400 Hz for different surface treatment conditions, including scribe spacing, scribe velocity and current. A current of 30 A corresponds to a beam power of 9.9 W and a power density of 560 MW/m<sup>2</sup> for a laser spot size of 18×10<sup>-9</sup> m<sup>2</sup>. A current of 24 A corresponds to a beam power of 6.1 W and a power density of 345 MW/m<sup>2</sup>. Positive % values in the results columns indicate an improvement in core losses, negative values indicate a deterioration.

Sample ID	Spacing (in.)	Velocity (in./s)	Current (A)	60 Hz	400 Hz
(a)					
Silicon alloys					
0.005 Magnasil N, fully processed					
J1	0.02	1	30	-24.30%	-65.58%
J2	0.02	1	24	-3.87%	16.73%
J3	0.02	0.75	24	1.61%	14.26%
0.018 M-36 fully processed					
K1	0.02	0.5	30	18.66%	...
K2	0.02	0.75	30	8.32%	...
K3	0.02	1	30	7.77%	6.94%
K4	0.02	0.75	30	11.66%	11.98%
0.018 M-43 fully processed					
L1	0.01	0.25	30	-0.37%	0.00%
L2	0.03	0.5	30	13.21%	...
L3	0.01	0.25	24	3.29%	...
L4	0.01	0.5	24	5.70%	...
L5	0.01	0.5	22	4.43%	...
L6	0.02	0.5	30	12.31%	...
L7	0.02	0.25	30	2.64%	...
L8	0.02	0.75	30	14.58%	...
L9	0.03	0.5	30	13.63%	...
L10	0.02	0.5	30	6.21%	...
L12	0.02	0.75	30	8.82%	14.40%
0.014 M-15, fully processed					
M1	0.02	0.75	30	2.67%	16.10%
M2	0.02	0.5	30	17.55%	16.66%
M3	0.01	0.75	30	5.98%	14.84%
M4	0.02	0.5	30	15.52%	15.97%
0.014 M-19, fully processed					
N1	0.02	1	30	...	11.09%
N2	0.02	0.75	30	...	15.48%
N3	0.02	0.5	30	18.73%	17.56%
N4	0.01	0.75	30	4.62%	18.16%
N5	0.03	0.75	30	-1.22%	13.54%
N6	0.01	0.5	30	12.13%	16.86%
N7	0.02	0.75	30	10.66%	17.52%
N8	0.03	1	30	...	12.46%
N9	0.01	1	30	...	18.58%
N10	0.03	0.5	30	...	-3.79%
0.022 MS1087, Magnetek, annealed					
O1	0.01	0.25	30	11.79%	4.36%
O2	0.01	0.5	30	6.66%	1.18%
O3	0.01	0.125	30	13.41%	-1.46%
O4	0.02	0.5	30	2.30%	0.94%
0.022 MS1414, Magnetek, annealed					
P1	0.01	0.125	30	9.65%	-10.45%
P2	0.02	0.25	30	5.36%	6.70%
(b)					
Carbon alloys					
0.024 temple CQ					
H2	0.01	0.25	30	3.64%	1.62%
0.024 MS1470, Magnetek, fully processed					
I2	0.01	0.5	30	6.21%	1.24%
I3	0.01	0.25	30	6.13%	3.62%
Cobalt alloys					
0.006 Hipercro 50, rotor grade, annealed					
D1	0.02	0.5	24	3.97%	...
0.014 Hipercro 50, rotor grade, annealed					
E1	0.03	1	30	4.09%	...
E2	0.015	0.75	30	4.48%	...
E3	0.01	0.5	30	-8.48%	...
E4	0.005	0.5	24	8.54%	0.41%
E5	0.005	0.5	24	8.05%	13.98%
E6	0.01	0.5	24	9.18%	...
E7	0.01	0.25	24	10.78%	3.04%
E8	0.0025	0.5	24	4.43%	...
Nickel alloy					
0.014 Carpenter 49, rotor grade, annealed					
C1	0.01	0.5	30	-19.41%	...
C2	0.01	1	30	-7.02%	...
C3	0.03	0.5	30	-2.85%	...
C4	0.06	0.5	24	36.60%	...
C5	0.06	0.25	24	3.24%	...
C6	0.03	0.25	24	3.12%	...
C7	0.06	1	30	-6.33%	...

The 0.45 mm sample M-15 had very smooth results for 400 Hz while the 60 Hz results were positive, but slightly more difficult to distinguish. The 400 Hz results were consistently at or beyond 15% reduction in core loss at high induction. This material gave one of the best examples of the possible core loss improvement that can be obtained as a result of laser domain modification. Some of the laser configurations for the 0.35 M-19 sample exhibited more than 18% improvement at 400 Hz. The results at 400 Hz again were very smooth and very consistent regardless of the laser parameters. The 60 Hz data was also positive, but not as smooth.

The 0.55 mm MS 1087 sample actually showed slightly better core loss improvement at 60 Hz than at 400 Hz which was the opposite of that observed with other samples.

### CONCLUSIONS

The results from this research showed a decrease in the core losses of silicon steels for various laser parameters. Domain modification through laser surface scribing has the potential to reduce the anomalous (or excess) eddy current losses that arise in lamination steels. This has resulted in core loss reductions of up to 18% in some materials, however the beneficial effects seem to be very material dependent. The practicality of using this process in routine manufacturing of magnetic core materials has yet to be investigated.

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