Reducing Core Losses in Amorphous $Fe_{80}B_{12}Si_8$ Ribbons by Laser-Induced Domain Refinement

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Abstract—**In transformer cores amorphous metallic ribbons are competitive substitutes for silicon-iron laminates due to their low values of core loss. Research has been conducted to further improve performance by using techniques that can reduce core losses in the metallic ribbons. One way of reducing core loss is to anneal the samples in a magnetic field. However, further reductions in core loss are possible by scribing the surface of the ribbons using a laser beam. The scribing pattern can lead to a refined domain structure and reduced excess loss. It has been found that under suitable processing conditions, core loss can be further reduced by as much as 20% by laser scribing.**

Index Terms—**Amorphous metals, core loss, laser scribing, transformer efficiency.**

I. Introduction

In the United States alone, power conversion inefficiencies are responsible for huge amounts of wasted energy every year. Most of this inefficiency is due to resistive losses, however iron losses (hysteresis and anomalous, or excess eddy current) are also significant. Werner and Jaffe [1] calculated that core losses in electric motors alone accounted for 45×10^9 kW.hr, or around $3 billion per year. That figure is now closer to 82×10^9 kW.hr. Even small fractional improvements in efficiency can lead to substantial savings. Traditionally, silicon-iron laminations are used for transformer cores. It has been shown that the anomalous loss of these materials can be reduced by laser treatment [2]–[4]. However, amorphous metallic glasses are gaining prominence because of the even lower core losses that can be achieved. It is possible to further improve performance of these materials by annealing, magnetic field annealing and laser treatment [5]. An automated core-loss measurement system has been designed and built. Results are reported here on improvements in core loss after treatment of the materials using the techniques described above.

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II. Core-Loss Measurements

Traditionally, core-loss measurements on flat strips of material required that the strips be formed into toroids around which excitation and pick-up coils could be wound. This approach is not only time consuming but also introduces unwanted stress into the samples. Even with careful handling, it is relatively easy to introduce stress into the metallic-glass ribbons, thereby altering their magnetic properties. A technique similar to that described by Khachan and Delamore [6] has been adopted so that measurements may be made on flat strips of material [7]. The process of comparing results from many different samples is then made considerably more convenient. To simplify the instrumentation, a sinusoidal applied field approach was used. Sinusoidal $B(t)$ conditions were considered, but because of the inherent inhomogeneity of B inside a ferromagnetic material, it was considered more reproducible to specify the waveform of the applied field which could be precisely controlled. The total core loss, P, is then given by

$$\mathrm{P} = \frac{f}{\rho} \int_0^{\frac{1}{f}} H(t) \frac{dB}{dt} dt, \qquad (1)$$

where ρ is the material density (kg/m^3), f is the excitation frequency, i.e. the fundamental of H, and P is the total power loss (W/kg). Measurements can be made at any frequency, although in this study 50 Hz and 1 kHz were used. Measurements were normally carried out at a number of induction levels up to the saturation point of the material.

III. Loss-Reduction Techniques

A. Annealing and Field Annealing

Annealing relieves residual stresses resulting in improved magnetic properties [8]. The annealing temperature is critical for the amorphous materials. Annealing at too high a temperature will lead to localized partial crystallization, the resulting magnetocrystalline anisotropy will have a detrimental effect on core loss. If the anneal temperature is too low then stresses are not adequately relieved. By experimentation, a temperature of $350 \pm 25°$C was found to give the best results, Fig. 1.

Annealing in the presence of an applied magnetic field leads to further improvements in magnetic properties [9]. Experiments were carried out by placing the samples in a solenoid within the annealing furnace. The field was varied by altering the solenoid current and resulting improvements in core loss are shown in Fig. 2. An applied

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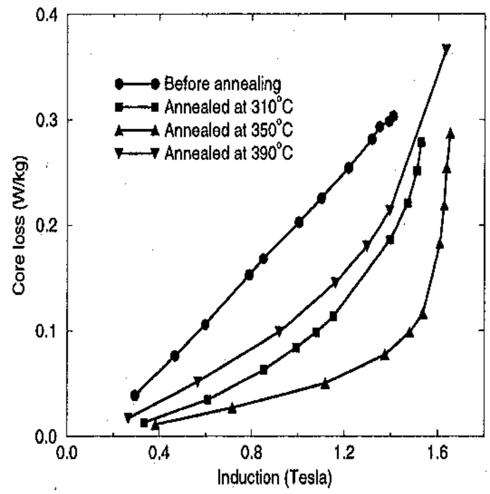

Fig. 1. Comparison of the effects of annealing temperature on core loss. Optimum reduction in core loss is obtained at around 350°C. Core-loss measurements were carried out at 1 kHz.

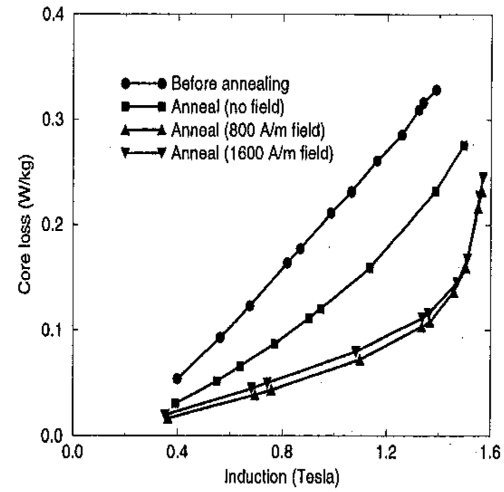

Fig. 2. The effects of a longitudinal field during annealing. A field of around 800 A/m was found to give the best results.

field of around 800 A/m was found to significantly reduce core losses. It was found that at higher field levels the reduction in core loss was not as great. At this stage we hypothesize that this is due to the dependence of magnetostriction on applied field; magnetostriction can be reduced, possibly even to zero, at higher field levels [10] resulting therefore in little benefit from the magnetic part of thermomagnetic annealing.

B. *Laser Scribing*

Additional reductions in core loss can be achieved by a carefully controlled treatment of the surface of the ribbons using a laser beam. The treatment pattern leads to a refined domain structure and reduced excess loss. The excess loss may account for typically 25-33% of the total core loss [11], so the improvements can be substantial. However, this method is unlikely to lead to improvements in hysteresis loss or classical eddy current loss. Therefore the technique is appropriate for materials with high levels of excess loss and progressively less appropriate for materials with lower excess loss. For optimum results, the laser-beam spot size should be as small as possible in order to create a sharp scribe pattern and well defined new domain-pinning sites. Obtaining a small spot size is difficult to achieve in practice, however, with the use of a gradient-refractive-index focusing lens, a spot diameter of around 150 μm was achieved. A Nd:YAG laser treatment system was constructed and used to modify the surface of the materials. In addition to continuous-wave, the laser was also operated in pulsed mode, in which a shutter was used to pulse the beam at repetition rates from a few tens to many thousands of times per second.

IV. Results of Laser Scribing

The effects of laser scribing were assessed under continuous and pulsed laser operation with core loss measurements being carried out at 50 Hz and 1 kHz. For continuous-mode operation experiments were carried out over a large array of measurement parameters including laser scribe speed, scribe spacing and laser power. Under the majority of conditions, improvements in core loss were insignificantly small. However, under the conditions noted in Table I, small improvements in core loss were observed at both 50 Hz and 1 kHz. The improvements become more substantial at higher induction levels, as shown in Fig. 3.

Table I. Optimum parameters for continuous wave and pulsed laser operation.

	Continuous wave	Pulsed
Scribe speed	317.5 mm/sec.	317.5 mm/sec.
Scribe spacing	0.254 mm	1.524 mm
Power	2.6 W	0.3 W (effective)
Pulse frequency	n/a	1 kHz

Under pulsed-mode operation and using the parameters of Table I, improvements in core loss were more significant, as shown in Figs. 4 and 5. Reductions in core loss were particularly significant at a field excitation frequency of 1 kHz, where improvements were seen over a broad range of induction levels. This is an important improvement over the continuous wave case where reductions in core loss were negligible at lower induction levels.

V. Conclusions

Thermal annealing of the amorphous metals at temperatures close to 350°C for around two hours was found to be most beneficial for reducing core losses. Both lower and higher temperatures were found to be less effective. The greatest improvement in core loss occurred while annealing at 350°C in an applied magnetic field of 800 A/m. This led to a 67% reduction in core loss as shown in Fig. 5.

The laser treatment of the amorphous metals showed some slight improvements in core loss at higher magnetic induction amplitudes. These improvements were typically

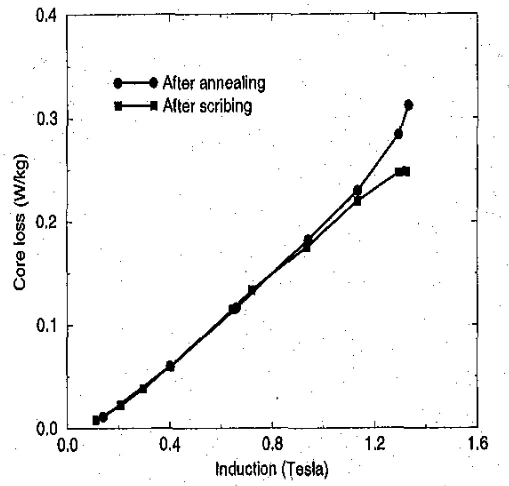

Fig. 3. Effect of continuous-wave laser scribing on core loss. Measurements were carried out at 50 Hz.

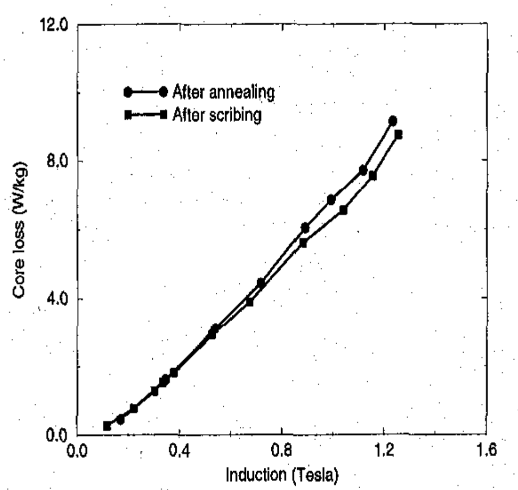

Fig. 4. Effects of continuous-wave laser scribing on core loss. Measurements were carried out at 1 kHz.

in the range 5-10% over and above improvements due to field annealing. However, the beneficial effects of laser scribing were restricted to a limited range of laser parameters. For example, treatment at a scribe speed of 317.5 mm/sec. gave improvements in core loss whereas at one-half of that speed there was a deterioration in core loss. Operating the laser in pulse rather than continuous mode gave the greatest improvements of around 20%.

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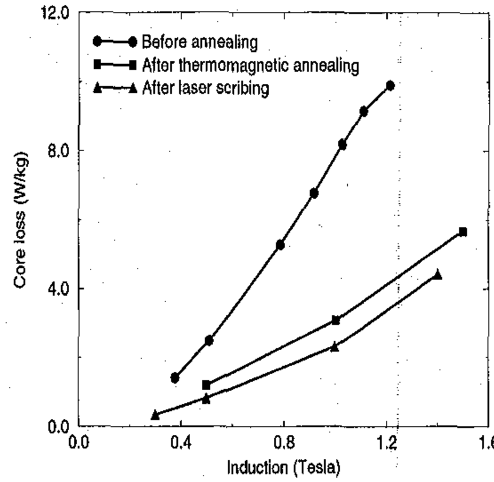

Fig. 5. Core-loss measurements at 1 kHz on the as-cast, magnetic-field annealed (350°C and 800 A/m) and laser surface scribed ribbons.

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