Further Improvement of Core Loss in Amorphous Alloys

T. Sato

Keywords
amorphous alloys, core loss, magnetic steels

1. Introduction

THE core losses of amorphous alloys are much lower than those of silicon steel, and thus the use of amorphous alloys as the core material for distribution transformers has contributed significantly to energy savings. However, amorphous metal transformers are not as widely used as expected. One reason is that traditional silicon steel has greatly improved in terms of core losses since the introduction of amorphous materials. The core losses of grain-oriented silicon steel has been reduced as much as 20% in the last decade. Furthermore, the possibility of greater reduction in core losses for silicon steel is reported by Arai et al.[1] On a laboratory scale, they have developed a low core loss silicon steel that is comparable to amorphous alloys.

Methods being used for further reduction of core losses in silicon steel include thinning, refining of magnetic domains, and surface polishing. Methods involving thinning and refining of magnetic domains contribute to reduce eddy current losses, and surface polishing reduces primarily hysteresis losses. The core loss minimized by Arai et al. was the result of a combination of metallurgical approaches and the above domain refining methods.

Also, for amorphous metals, several methods have been proposed to improve core losses. Oblique directional magnetic field annealing[2] and the introduction of linear crystallized regions[3,4] are means unique to amorphous metals. These methods however do not exhibit a significant effect on core loss reduction, because of the small fraction of eddy current losses. Domain refining methods such as mechanical scribing[4,5] also are not effective in a lower frequency range, unlike silicon steel.

Previous studies on loss reduction have been conducted using conventional amorphous alloy ribbon of 20 to 30 µm thickness. Thick ribbon over 50 µm was difficult to make by conventional methods. A recent study[6] has made it possible to obtain 100-µm thick amorphous ribbon. The thick amorphous ribbon exhibits lower hysteresis losses and higher eddy current losses compared to conventional thin ribbon. Therefore, the core loss of amorphous metal is expected to be reduced further by using the methods that have proven effective for silicon steel.

This article studies the possibility of further improvement in core losses by applying laser scribing, tension, and chemical polishing to thick amorphous ribbon.

T. Sato, Advanced Materials & Technology Research Laboratories, Nippon Steel Corporation, Japan.

2. Laser Scribing

2.1 *Laser Scribing after Annealing*

Figure 1 shows the effect of laser scribing on core losses and permeability and its ribbon thickness dependence in an amorphous $Fe_{80.5}Si_{6.5}B_{12}C_1$ alloy.[7] Scribing was made with a YAG pulse laser, with a power of 0.5 W, scanning spacing of 5 mm, and spot interval of 240 µm. The samples were field annealed prior to laser scribing (the anneal/laser treatment). As shown in Fig. 1, although core losses are generally higher for thicker ribbon before laser treatment, on laser scribing, they became constant with the thickness. The more significant effect on core losses of thicker ribbon is caused by a larger fraction of the eddy current losses. On the contrary, degradation in permeability is less for thicker ribbon. This is favorable from a practical point of view.

Figure 2 indicates the effect of laser power on core losses for 65-µm thick ribbon.[7] Core losses were minimized at 0.5 W with a reduction of 35%. This rate of improvement is greater than that for silicon steel. Permeability decreases with increas-

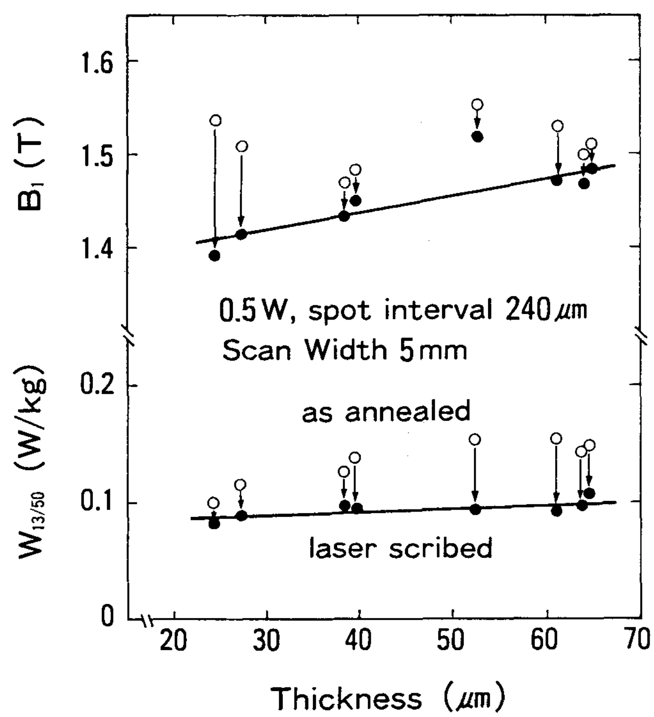

Fig. 1 Effects of laser scribing on magnetic properties and their thickness dependence on the anneal/laser treatment. B_1, induction at 1 Oe; $W_{13/50}$, core loss at 50 Hz and 1.3 T. Open circles represent properties before laser treatment.

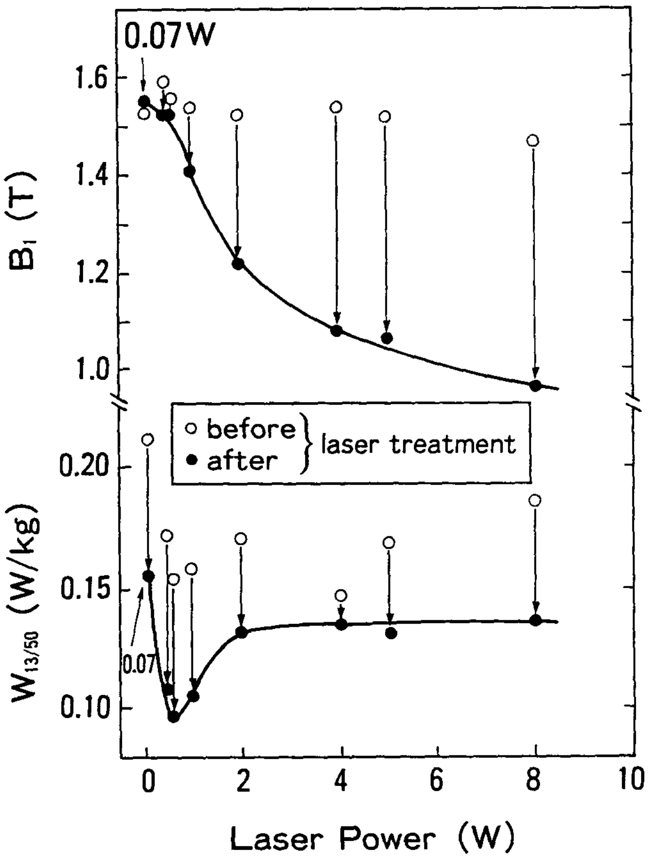

Fig. 2 Effects of laser power on magnetic properties following the anneal/laser treatment.

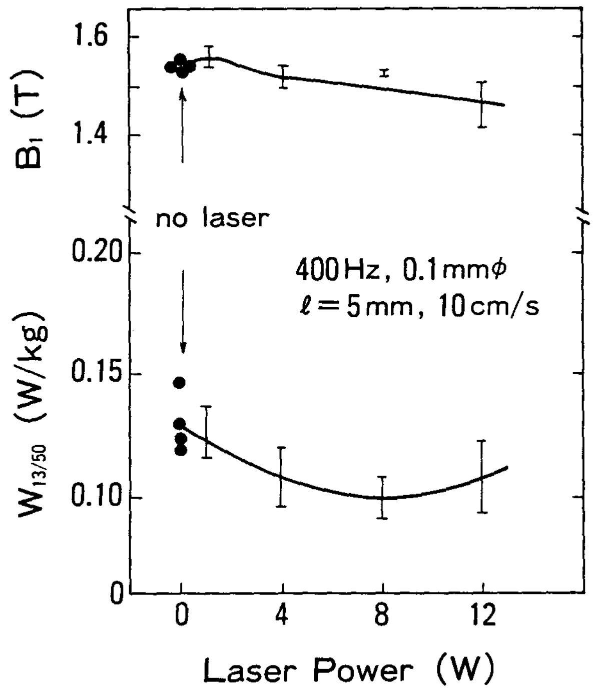

Fig. 3 Effects of laser power on magnetic properties following the laser/anneal treatment.

ing laser power, but the degradation in permeability at a power of 0.5 W is as small as 3%, and thus acceptable in practical use.

2.2 *Laser Scribing prior to Annealing*

Figure 3 shows the effects of laser scribing before annealing (the laser/anneal treatment).[7] The magnetic properties were measured on samples annealed at 380 °C for 60 min after laser treatment. As shown in Fig. 3, laser scribing prior to annealing is also effective in reducing core losses. This is practically significant, because laser treatment is applicable for wound cores. In silicon steel, the application of laser scribing is limited to stacked cores. The characteristic differences between the two laser treatments are as follows:

- Ten times more power is required to achieve the optimum properties in laser treatment prior to annealing.
- The degree of degradation in permeability is much less than that for laser treatment after annealing.
- The freedom of laser power applied is much wider for laser treatment prior to annealing.

The reason that laser scribing prior to annealing is effective in amorphous alloys is probably due to the use of a much lower annealing temperature compared to the stress relief annealing temperature used for silicon steel. Stresses introduced with the use of high power levels are affected by annealing. Furthermore, subsequent annealing eliminates excess stresses that are ineffective for domain refining and consequently minimizes the decrease in permeability.

To clarify the mechanism of core loss reduction, the domain pattern was observed with a scanning electron microscope (SEM). Figure 4 demonstrates that a thick amorphous ribbon of 65 μm has domains that are several times wider before annealing than the conventional thin ribbon of 30 μm, suggesting large eddy current losses.[7] Domains of laser-scribed thick ribbon become as narrow as those of thin ribbon, regardless of the order of laser treatment and annealing. These results are consistent with the changes in measured eddy current losses.

As mentioned above, the effect of laser scribing is greater in thicker ribbon, but the core losses of thick ribbon are originally greater than those of thin ribbon, due to its higher eddy current losses. Therefore, one cannot expect a substantial effect due to the use of laser scribing.

3. Application of Tensile Stress

Application of tensile stress is well known to greatly reduce the core losses of silicon steel. Therefore, it is necessary to examine its effect on amorphous materials. Figure 5 shows the effect of tension on core losses and permeability for various ribbon thicknesses. The alloy composition is the same as the one used in the section on laser scribing, and the samples were field annealed. As shown in Fig. 5, tensile stresses exhibit deleterious effects on rather than improving core losses. To interpret the increase in core losses, the core losses were separated into hysteresis and eddy current losses. The results for three dif-

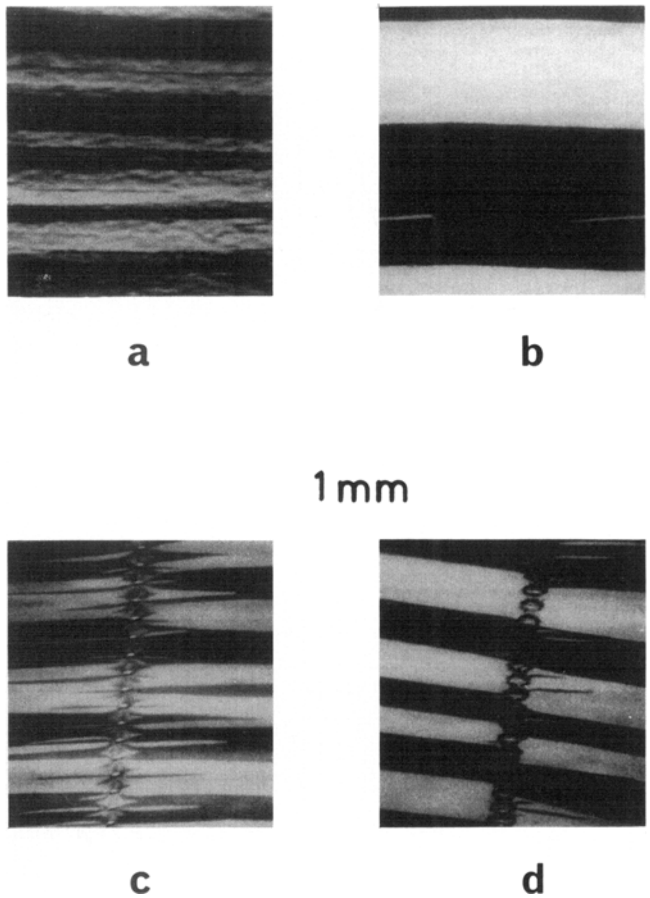

Fig. 4 Domain patterns observed by SEM. (a) 30 μm, annealed. (b) 65 μm, annealed. (c) 65 μm, laser scribed after annealing. (d) 65 μm, annealed after laser scribing.

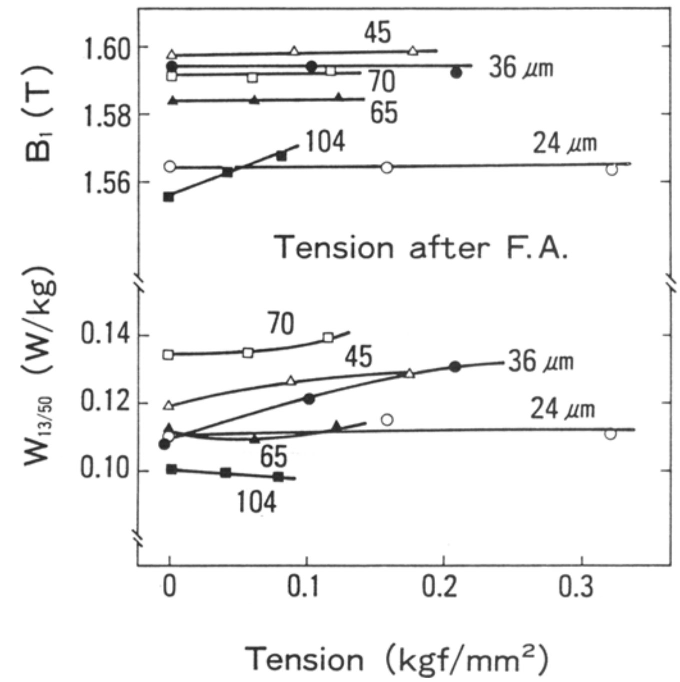

Fig. 5 Effect of tensile stress on magnetic properties.

ferent thicknesses is shown in Fig. 6. The increase in core losses for 24 and 70 μm is due to an increase in eddy current loss. One can presume that the increase in eddy current losses results from the coarsening of principal domains due to the disappearance of surface-free poles. Note also that in silicon steel the effect of tensile stress does not appear on the ideal Goss orientation, but on the orientations with a [001] axis tilted off the ribbon plane. Amorphous material has very weak perpendicular anisotropy after field annealing, and thus, surface poles can easily be eliminated by tension, unlike the case of silicon steel. As a result of the disappearance of free poles, it becomes unnecessary to lower the magnetostatic energy further by refining the domain structure. From the above results, the author concludes that tensile stresses are useless for amorphous metals.

4. Surface Polishing and Thinning

Because the methods of core loss reduction proposed to date for amorphous alloys have not had a significant effect, it is necessary to consider different approaches. The effects of surface polishing and thinning were examined in view of hysteresis loss reduction, which is a major component of core losses for amorphous material. Surface polishing was conducted by chemical etching. Chemical etching also reduces the ribbon thickness and therefore is expected to decrease eddy current losses at the same time.

Figure 7 compares changes in core losses and hysteresis losses with the ribbon thickness on chemically thinning ribbons of 25 and 60 μm from both sides of the ribbon.[9] For thin ribbon, the core loss at 50 Hz and 1.3 T, $W_{13/50}$, decreases rapidly, as thinning begins, reaches a minimum around 20 μm, and then increases again. On the other hand, the core loss of thick ribbon decreases slowly, but continues decreasing in a wide thickness range down to 10 μm, consequently reaching a much lower minimum. The minimum core loss of 0.04 W/kg obtained at 10 μm for a ribbon of 60 μm is half the lowest value previously reported and approximately 30% of the lowest value (0.13 W/kg) reported for silicon steel. This result experimentally verifies the prediction that amorphous metal should be much lower in core losses than silicon steel, considering its higher resistivity and much lower anisotropy.

The key point that made it possible to reach such a low loss is the use of thick ribbon as a starting material. As shown in Fig. 7, for thick ribbon, the hysteresis loss remains constant at a very low value until the ribbon is thinned to 10 μm. Thus, the eddy current decrease with the thickness reduction is directly reflected in the reduction of core loss. On the contrary, the hysteresis loss of thin ribbon begins to increase at 20 μm. The rate of increase is greater than the rate of reduction of eddy current losses, and as a result, the core loss begins to increase again when the ribbon is etched below 20 μm.

To clarify which side of the ribbon contributes more to core loss reduction, the ribbon was etched from one side only. Figure 8 shows that, for either thickness, etching the roll side exhibited much larger reduction than etching the free side.[9] The

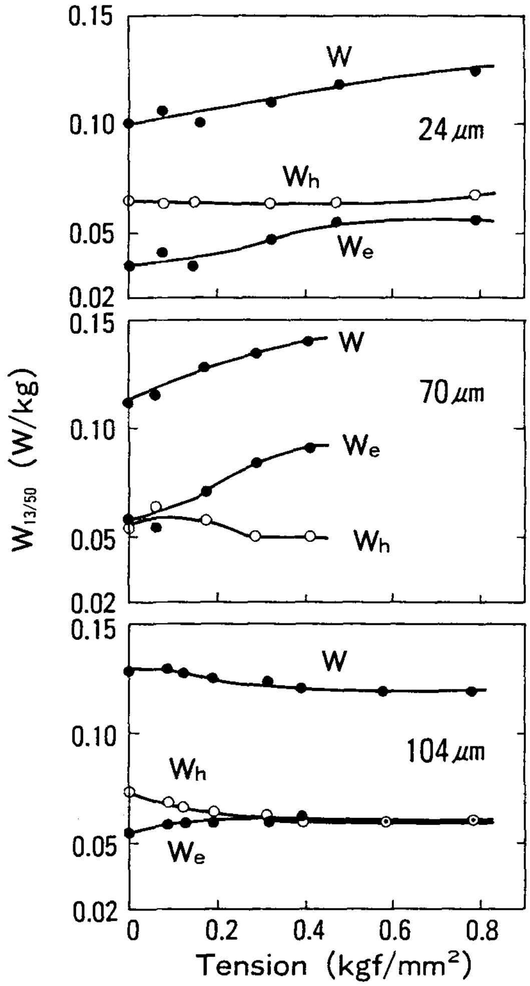

Fig. 6 Effect of tensile stress on hysteresis loss (W_h) and eddy current loss (W_e). (W denotes core loss or total loss.)

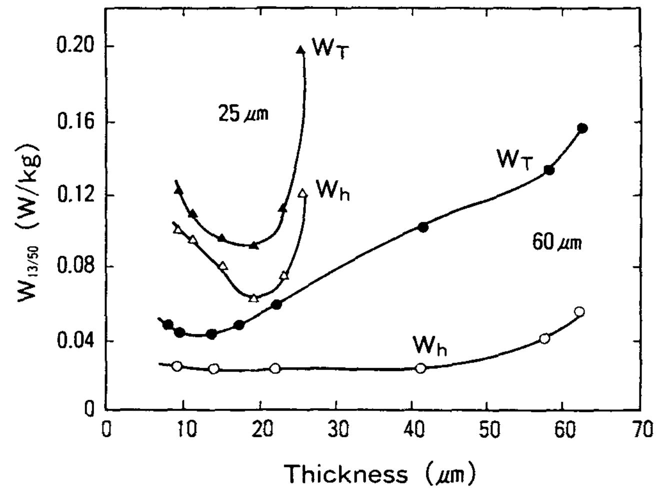

Fig. 7 Changes in core loss (W_T) and hysteresis loss (W_h) as a function of ribbon thickness for two-sided etching.

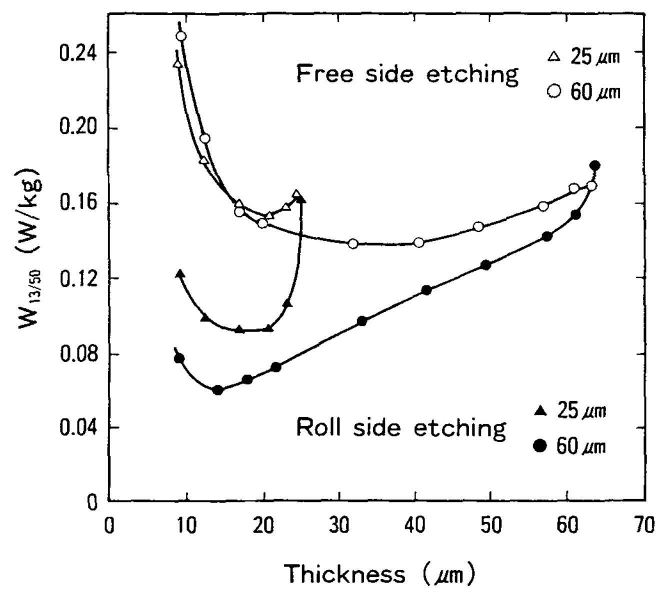

Fig. 8 Changes in core loss as a function of ribbon thickness for one-sided etching.

minimum value of the core loss of thick ribbon is less than that of thin ribbon in etching the roll side, but the difference in minimum loss is reduced considerably compared to etching both sides. On the other hand, the effects of etching the free side appear to be almost independent of initial thickness. As shown in Fig. 8, for the two thicknesses, the core loss curves are similar for thicknesses less than 20 µm. The large reduction in the core loss by etching the roll side, as shown in Fig. 9,[9] results from the hysteresis loss remaining low and decreasing thickness. However, etching the free side does not contribute to the reduction of hysteresis loss, but rather increases the hysteresis loss in a thickness range below 40 µm, as shown in Fig. 10.[9] Figures 9 and 10 also show that the eddy current losses decrease monotonously with decreasing thickness, regardless what side of the ribbon is etched.

The difference in the behavior of hysteresis loss between thin and thick ribbon with etching is probably due to the difference in structural homogeneity inside the ribbon in addition to surface roughness. Thick ribbon remains in a temperature range above the glass transition temperature, T_g, for a longer period of time and therefore has a longer time for structural relaxation after solidification. This factor would contribute to lowering the hysteresis loss of thick ribbon, because the inhomogeneity formed above T_g could be difficult to remove by annealing, which is usually carried out at temperatures much lower than T_g.

5. Estimation of Core Loss

The results of the present study indicate that chemical thinning of thick ribbon is the best way to lower core loss. A core loss ($W_{13/50}$) of 0.04 W/kg was obtained by etching a thick ribbon of 60 µm, with a thickness reduction of from 60 to 10 µm. Such a great thickness reduction is not practical, but the above

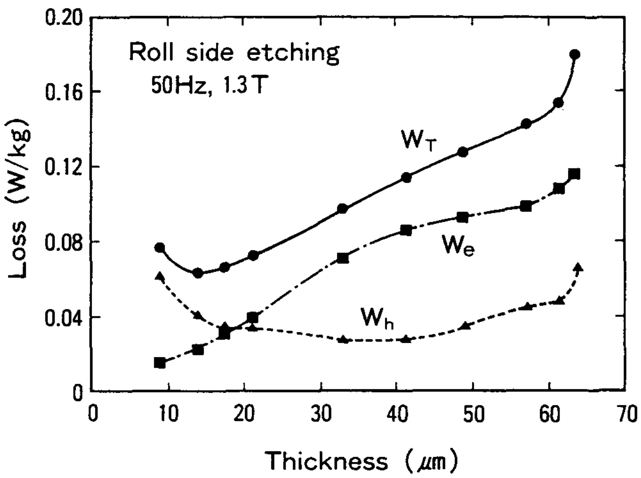

Fig. 9 Changes in hysteresis loss (W_h) and eddy current loss (W_e) for roll-side etching.

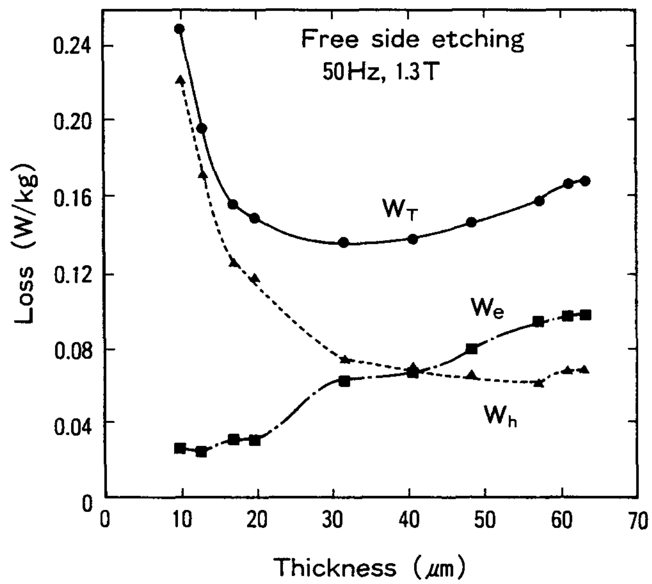

Fig. 10 Changes in hysteresis loss and eddy current loss for free-side etching.

experimental results are useful in estimating the achievable core loss of amorphous alloys. On the basis of the experimental results, the possible core losses are calculated below.

A hysteresis loss of 0.02 W/kg has been already achieved at 40 μm, as shown in Fig. 7. Eddy current loss for a thickness of 40 μm can be calculated from classical eddy current loss, $W_{ce} = (\pi Bft)^2/(6\rho\gamma)$, and anomalous factor, $\eta = 1.63(2L/t)$, where B, f, and t are magnetic induction, frequency, and ribbon thickness, respectively, and ρ, γ, and $2L$ are density, resistivity, and domain width, respectively. Substituting $B = 1.3$T, $f = 50$Hz, $t = 40 \times 10^{-6}$m, $\rho = 7.3 \times 10^3$ kg/m^3, $\gamma = 1.3 \times 10^{-6}\Omega\cdot$m yields $W_{ce} = 1.2 \times 10^{-3}$ W/kg. If domain widths can be refined to 1 mm, the anomalous factor is 40, and thus, the eddy current loss is approximately 0.05 W/kg. The addition of 0.02 W/kg (hysteresis loss) yields 0.07 W/kg as the total loss. This value is obtained at a thickness of around 25 μm in the course of chemical thinning. To achieve a minimum value of 0.04 W/kg as in Fig. 7, the domain widths must be refined to 0.5 mm. The domain width of 1 mm is attained by laser scribing, and thus, a width of 0.5 mm is not unrealistic. Furthermore, if domain widths can be refined to 0.1 mm with constant hysteresis loss, a total loss of 0.025 W/kg can be achieved.

There may be room for improvement not only in eddy current losses, but also for hysteresis losses. It may be possible to reduce the current value of 0.02 W/kg by half. If so, a core loss of 0.015 W/kg can be achieved. This value is only one ninth of the best value reported for silicon steel. Therefore, with respect to core losses, the superiority of amorphous materials over silicon steel will continue in the future.

References

1. K.I. Arai, K. Ishiyama, and H. Mogi, *IEEE Trans. Magn.*, Vol MAG-25, 1989, p 3949
2. H. Fujimori, H. Yoshimoto, and H. Morita, *IEEE Trans. Magn.*, Vol MAG-16, 1980, p 1227
3. T. Kan, H. Shishido, and Y. Ito, Japan Institute of Metals, Annual Meeting, Apr 1981, p 157
4. K. Narita, J. Yamazaki, H. Fukunaga, and H. Hata, Proc. 4th Int. Conf. Rapidly Quenched Metals, Vol 2, Ed. T. Masumoto and K. Suzuki, The Japan Institute of Metals, 1982, p 1001
5. R.F. Krause and F.E. Werner, *IEEE Trans. Magn.*, Vol MAG-17, 1981, p 2686
6. T. Sato, T. Yamada, and T. Ozawa, Anales de Fisica, Series B, Vol 86, 1990, p 148
7. T. Sato, T. Yamada, and T. Ozawa, *Rapidly Quenched Metals V*, Vol 2, 1985, p 1643
8. T. Nozawa, T. Yamamoto, Y. Matsuo, and Y. Ohya, *IEEE Trans. Magn.*, Vol MAG-14, 1978
9. T. Sato and T. Yamada, *IEEE Trans. Magn.*, Vol MAG-28, 1992, p 2775