Reducing Core Loss

OF SEGMENTED LAMINATIONS

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Management Summary

The recent trend towards using segmented laminations as a means to increase slot fill and facilitate automated fabrication of electric machines comes with a penalty of increased core loss at the segment joints. Segmentation of laminations has been reported to increase some losses by up to 50%, but there has been very little information published for medium or small motor applications. This paper summarizes the root causes of this change in loss and offers choices to reduce the effect. An advanced finite element analysis is used for calculation of the electromagnetic fields in the vicinity of the joints of the laminated steel, and takes into account the effect of the punched-edge joint and compressive stress on the core loss properties. It is shown that the increase in core loss results from several factors caused by the segmented joint, including degraded material conditions at the joint, increased amount of punched edge and compressive stress. The losses can be reduced by lamination alignment, stress-relieving the punched edges and a very small amount of core insulation at the joint. Reduction of the effect of compressive stress on the losses remains as a trade-off to be taken into account based on the user's assembly techniques.

Introduction

Motor and generator stators and rotors are usually manufactured using a stack of one-piece laminations, made by punching the desired pattern from one large sheet of steel. A variation of this manufacturing technique that has recently been gaining popularity is to punch each lamination tooth as an individually segmented piece and to later position the pieces into the desired slot-tooth pattern. After the segmented pieces are in position, the geometric pattern and magnetic circuit are approximately the same as for one-piece laminations (Fig. 1).

While the one-piece lamination method offers the advantage of assembly simplicity, the segmented lamination method also offers the potential of:

- Reduced raw material waste
- Lower capital cost for the punching equipment and tooling
- Choices in coil insertion methods and increased slot fill
- Some new choices in materials and automation

(*See Figure 2 for examples of an automated winding process and post-assembly stator.*)

A significant amount of literature has been published about losses associated with lamination joints in power transformers, and this forms a good foundation for the present work (Refs. 4–9). Similar discussion can be found for very large electric machines, where a lamination piece contains several teeth (Refs. 10–11). For both applications, the literature reports many variations of lamination joints, often with some degree of overlap employed during core build-up. The effect on the material core loss behavior by the cutting or forming process used to make shaped laminations is less well documented (Refs. 12–13).

Minimizing power losses of the motor core is one key ingredient for high-efficiency electric machines. However, the impact on motor design, particularly core losses, for this construction method has not been widely discussed in the literature. Therefore, it is necessary to look at reports of similar fabrication techniques to gather an overall understanding of the situation in motors.

The effect of compressive stress has also been widely discussed (Refs 14–18), but is not as yet well understood by motor designers. In fact, the effect of compression of lamination joints on eddy currents at the joint edges in motors appears to be undocumented. All these factors are simultaneously present in the segmented lamination motor, and a better understanding of the total effect on core loss for this type of lamination assembly in the electric machine environment is needed.

This paper discusses the causes of these changes in core loss and presents choices to reduce the effect. An advanced, 2-D finite element analysis is used for calculation of the electromagnetic fields in the vicinity of the joints of the laminated steel, and takes into account the effect of the punched-edge joint and compressive stress on the core loss properties.

Core Losses Particularly Applicable to Segmented Laminations

The segmented lamination has an additional cut edge in the back-iron area of the core, and all cutting methods cause some increase in losses. It is widely believed that laser cutting does not affect core losses, but this is not the case. In fact, laser cut laminations can have 20% higher losses at flux densities around 0.5 T, but the negative effect tends toward a negligible difference for flux densities over 1 Tesla (Ref. 13). The remainder of this paper will focus on lamination pieces made with non-oriented, fully processed electrical steel material, and using the punch and die process.

Inevitably, the punch-and-die method of making an electric machine laminated core results in an increased power loss characteristic (i.e., W/kg) because it requires metal displacement that leaves residual internal stress, cold-work regions and dislocated magnetic domains within the affected region. The inherent burr edge is a key cause of eddy current losses. For laminations made by punching sheet steel, the region of increased loss can spread up to several millimeters from each punched edge (Ref. 19). Segmented laminations always have a larger volume of degraded, higher-loss material than equivalent, unsegmented laminations.

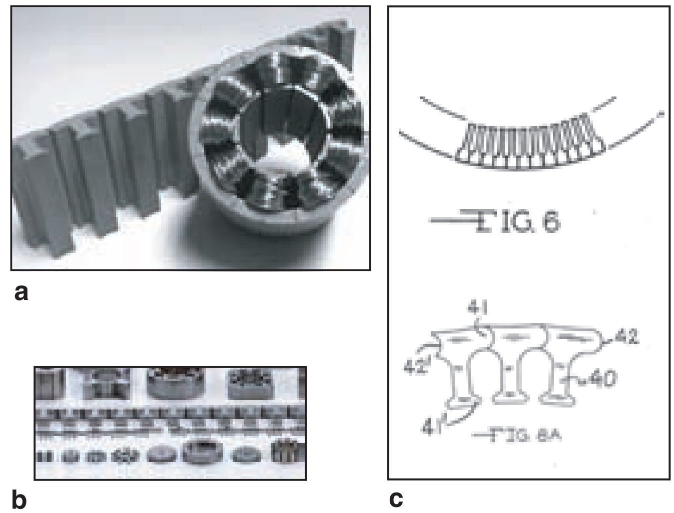

Figure 1(a)—Hinged segmented lamination, pieces rolled into position (Ref. 1). Figure 1(b)—Segmented lamination (straight row of teeth laying side-by-side) rolled into position by 'edge-bending,' narrow bridges between segments (Ref. 2). Figure 1(c)—Segmented lamination pieces, stacked for axial length, then placed in position and held by stator housing (U.S. Patent 5,212,419; Ref. 3).

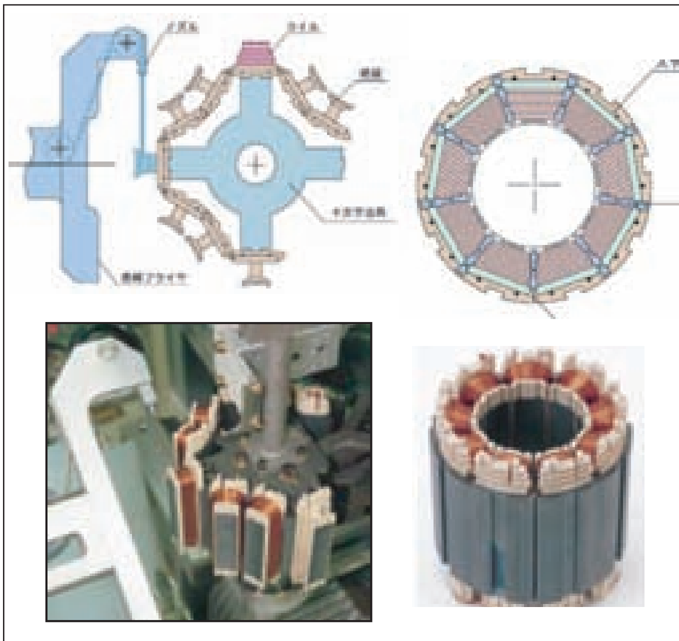

Figure 2—Segmented laminations.

A further potential cause of increased loss due to segmented laminations is the potential for eddy current loss at the edge-to-edge butt joint used to adjoin the segments. Any non-insulated surface or burr edges along the face of the segment joint can provide a path for eddy currents when pressed against each other, such as when under compression due to the housing. However, the amount of contact and the effective resistivity of such a joint in segmented

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lamination motors appear to be neither discussed nor quantified in the literature.

Analytic Calculation of Core Losses

The modeling and calculation of core losses has been extensively reported in the literature, including efforts to account for losses associated with the high frequency harmonics of switch-mode PWM inverters. There are two popular methods for calculating core losses, which account for the dependency of losses on flux density, B, and excitation frequency, f, including harmonic losses. One is based on the Steinmetz formulation, (Eq.1), with separate terms for hysteresis loss and eddy current loss (Refs. 20–23). The second expression is based on a single term using the product of flux density and frequency with non-integral exponents (Eq. 2; Refs. 24–26).

Steinmetz (1)

$$P_{fe} = (K_h f\ B^x + K_{ec} f^2 B^2)\ V_{fe} \quad \text{Watts} \tag{1}$$

Non-integral Exponents: (2)

$$P_{fe} = K_{fe} f^m B^n V_{fe} \quad \text{Watts} \tag{2}$$

The K's are coefficients experimentally obtained for each material, x varies from about 1.6 to 2.1, and V_{fe} is the core volume in appropriate units. It is very important to note that to obtain high accuracy, including for heavy saturation and for the effects of harmonics, these coefficients will vary as functions of frequency, flux density, temperature, minor loops and, especially, the localized rate of change of the flux density, dB/dt. When these characteristics are explicitly included in Equations 1 or 2, the expressions become somewhat more complex (Refs. 27–31), although the essence remains the same. An added term, "excess loss," is included and varies as the 1.5 power of frequency and flux density:

$$P_{fe} = P_h + P_{ec} + P_{excess} \quad \text{Watts} \tag{3}$$

$$P_{fe} = (K_h f\ B^x + K_{ec} f^2 B^2 + K_{excess} f^{1.5} B^{1.5})\ V_{fe} \quad \text{Watts} \tag{4}$$

The effect of the segmented laminations on core loss appears to be three-fold:

- A change due to the internal stress and dislocation of domains at the additional punched edges, due to the punching and compressive force by the housing, which changes K_h
- A change in losses due to the contact of the conductive surfaces of the

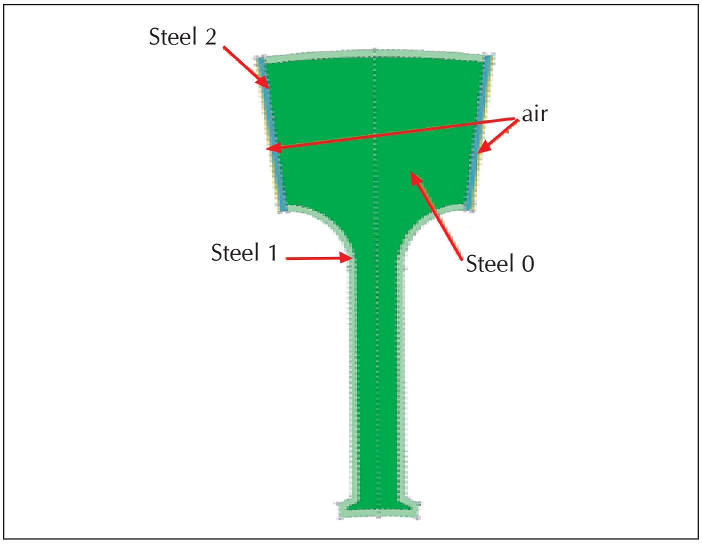

Figure 3—Model of segmented lamination.

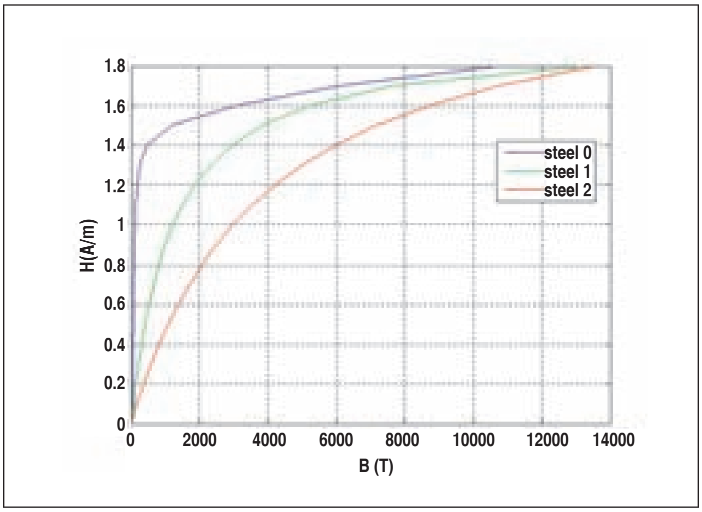

Figure 4—BH curves of:
i) Steel 0–Original, pre-punched.
ii) Steel 1–punched.
iii) Steel 2–punched and under compressive stress.

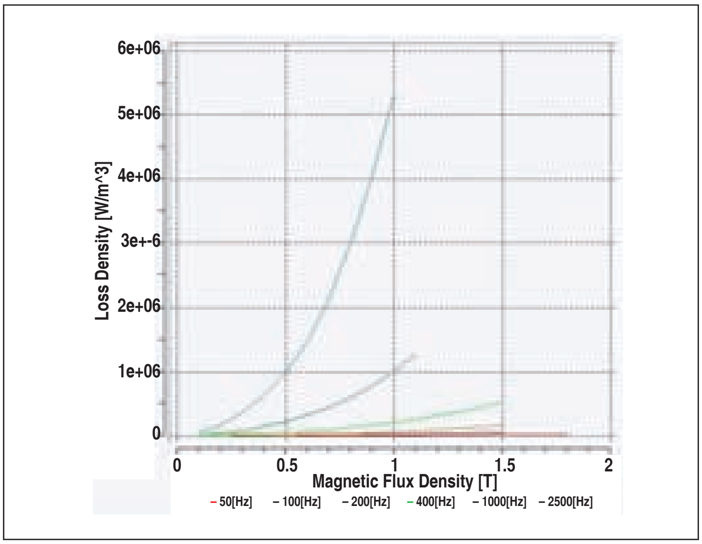

Figure 5—Iron loss of Steel 0.

edges, providing a possible new path for eddy-currents, which changes K_{ec}

- A change in the effective magnetic path due to the butt-joint interface, which varies with the circumferential compression of the segments, which changes K_{excess}

Preliminary analysis and testing results indicate each of the loss mechanisms has some influence, but, in total, they can be essentially negligible with good manufacturing technique. The effect on reluctance impacts the losses by changing the flux density magnitudes, which can change performance slightly, so the effect on the overall magnetic circuit is somewhat more important. The change in magnetic circuit due to the butt-joint edges, which can amount to a small additional air gap in the flux path, leads one to the conclusion that this technique is probably best suited for permanent magnet machines and similar machines relatively insensitive to an increase in the effective air gap.

FEA Calculation of Magnetic Field

A study was conducted of several segmented lamination configurations modeled using *JMAG Studio* (Ver 9) finite element analysis (FEA) software. For this first attempt at evaluating segmented laminations made by punching, the methodology of 'Cut Edge Length' was used (Ref. 13). This is based on the concept that the change in core loss due to the punch process can be approximated by taking account of the length of the punched edge of the lamination pieces, hence the amount of damaged volume. In particular, this high-stress, dislocated domain area has a degraded BH curve and higher losses than the pre-punched material.

For the segmented lamination, we can identify three distinct regions of differing material property (Fig. 3; Ref. 12). The region identified as 'Steel 0' has the original, undamaged non-oriented steel characteristics. The region identified as 'Steel 1' is the punched edge, has a degraded BH curve, and is modeled with 15% higher loss density than Steel 0. The region identified as 'Steel 2' is the punched edge under compressive stress, has a further degraded BH curve, and is modeled with 20% higher loss density than Steel 0. The 'air region' is initially set to be the same as Steel 2 material, and in later studies will be changed to represent an insulation coating on the edges of the laminations.

The Steel 1 region is set at 0.5 mm wide in this simulation, although a valid argument could be made, based on Ossart's work, that

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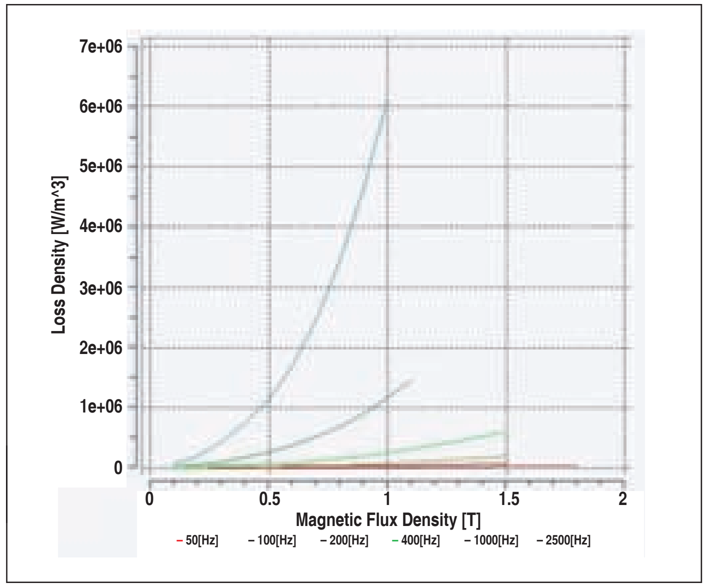

Figure 6—Iron loss of Steel 1 is 15% higher than Steel 0.

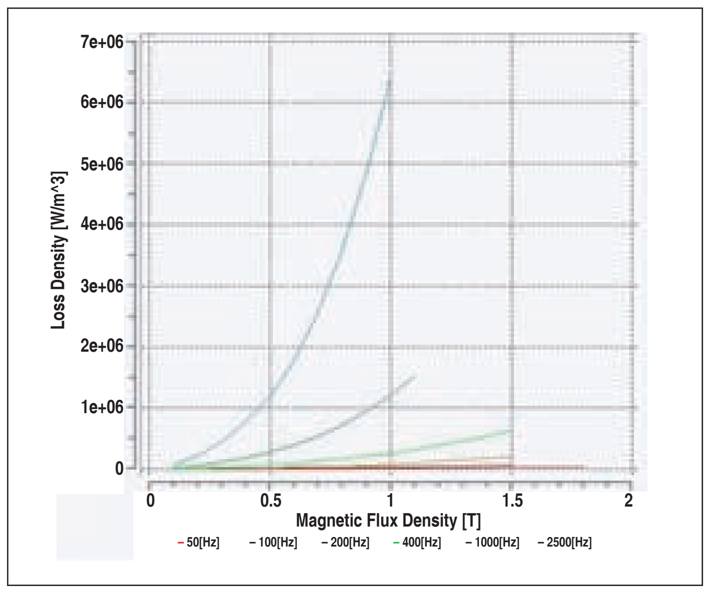

Figure 7—Iron loss of Steel 2 is 20% higher than Steel 0.

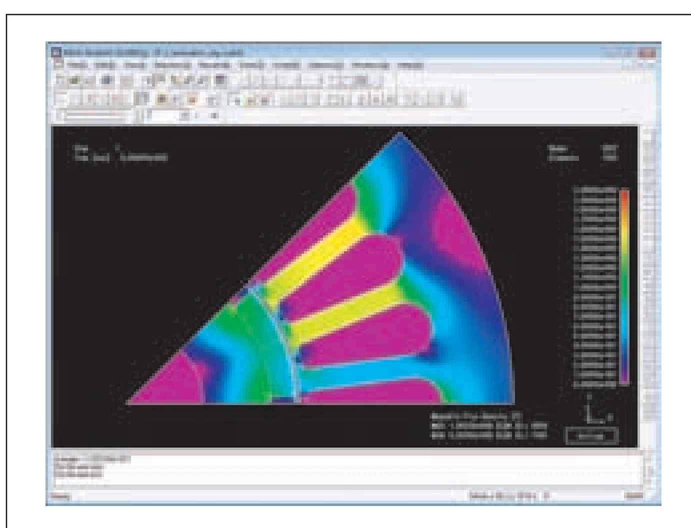

Figure 8—Flux density: original lamination, no segments.

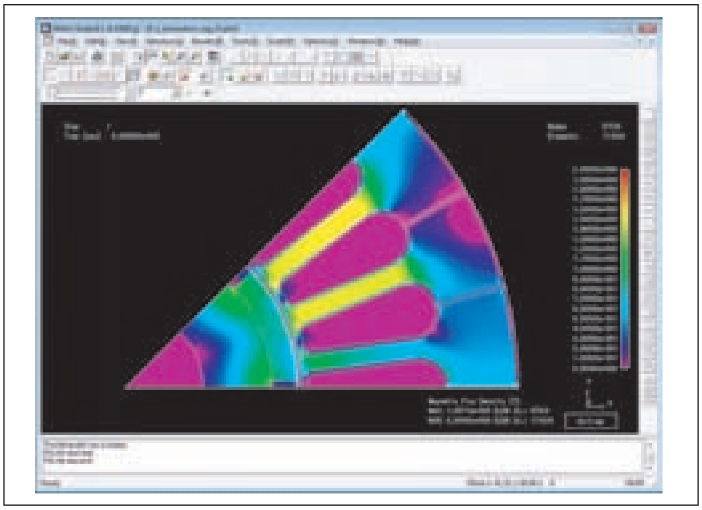

Figure 9—Flux density: Type I—Radial-line segment joint.

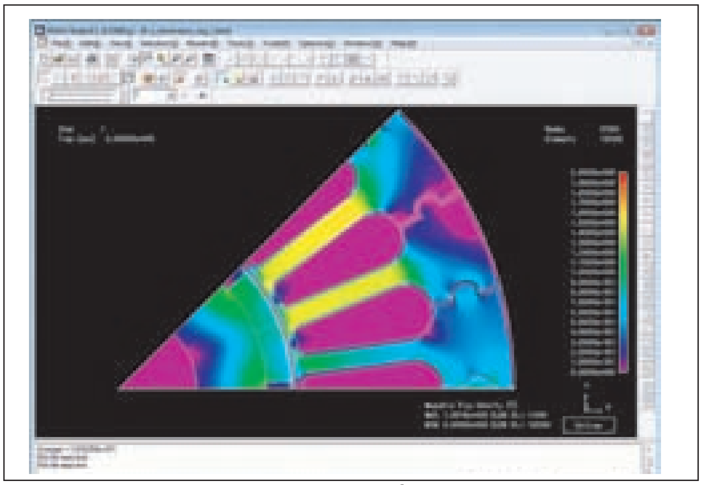

Figure 10—Flux density: Type II—Half-round segment joint.

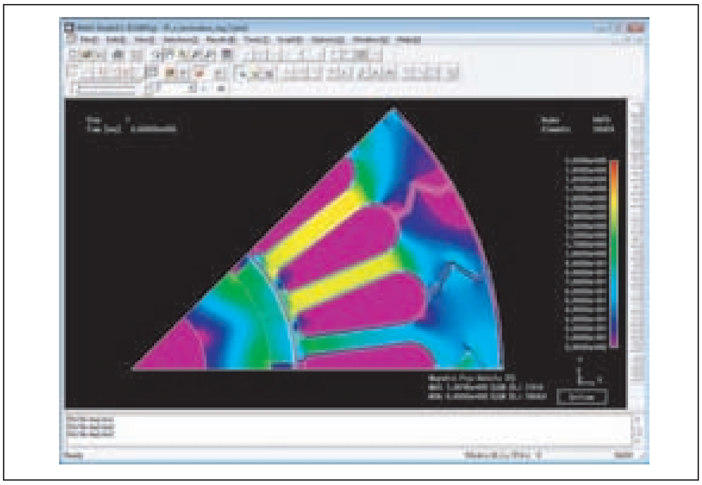

Figure 11—Flux density: Type III—Triangle miter segment joint.

Table I—Calculated Torque		
Lamination	Torque	Variation from Original
Original, no segments	16.69 Nm	-
Type I—Radial-line segment joint	16.25 Nm	-2.6%
Type II—Half-round segment joint	16.30 Nm	-2.3%
Type III—Triangle miter segment joint	16.30 Nm	-2.3%

this could be up to 3 mm wide. Arshad states the width of the degraded material is approximately equal to the lamination thickness. Figure 4 shows the BH curves, and Figures 5–7 show the loss density curves, used in this simulation. The basis for the BH curves is in the references already cited. The loss curves are derived from the Steinmetz equation given in Equation 2.

Figures 8–11 show the flux density distribution for the four lamination configurations that have been modeled: 1. No segments; 2. Type I—Radial line segment joints; 3. Type II—Half-round segment joints; and 4. Type III—Triangle miter segment joints.

Analysis of FEA Results

After determining the magnetic field, the torque was calculated within the FEA software using what is essentially a virtual work method. The results are shown in Table I. As expected, there is a slight decrease in torque for the segmented lamination models, about 2–3%.

The FEA software determines the loss density for every element in the FEA model, and then sums the losses of all elements to determine the total loss in Watts. Figures 12–15 show the loss density for the four cases. Table II lists the total losses.

Conclusion

This is an initial attempt to quantify the added losses associated with segmented lamination cores, and additional simulations are ongoing. It is shown, using reasonable assumptions, perhaps even overly optimistic, that an increase in core loss results when the segmented joint lamination is used. Several factors contribute to the loss, and the methodology proposed and used here can readily be used to separate the losses. The losses can be reduced by lamination alignment to reduce eddy currents, stress-relieving the punched edges and adding a very small amount of core insulation at the joint. Reduction of the effect of compressive stress on the losses remains as a trade-off to be taken into account based on the user's assembly techniques. Results of more extensive models, with different joint configurations and conditions, will be reported in the future.

An important observation is that the segmented lamination technique is probably best suited to electric machines where the size of the effective air gap is insensitive to small variations, as in permanent magnet machines. Also, it may not be fully beneficial when the material removed to make the stator lamination is useful to make the core of the rotor, as for induction machines where the center hole can be used to make the slotted core for the squirrel cage or wound rotor.

References

1. *Electrical Manufacturing & Coil Winding News*, pg. 3, 2004.
2. Mitsui High-Tec website (Nov, 2004): *http://www.mitsui-high-tec.com*
3. Fisher, G.A. and J. T. Jacobs. Lightweight High Power Electromotive Device, U.S. Patent No. 5,212,419, May 18, 1993.
4. Moses, A.J., B. Thomas and J. E. Thompson. "Power Loss and Flux Density Distributions in the T-Joint of a Three-Phase Transformer Core," *IEEE Transactions on Magnetics*, Vol. 8, No. 4, Dec., 1972, pp. 785–790.
5. Moses, A.J., B. Thomas and J. E. Thompson. "Spatial Variation of Localized Power Loss in Two Practical Transformer T-Joints," *IEEE Transactions on Magnetics*, Vol. 9, No. 4, Dec., 1973, pp. 655–659.
6. Jones, M.A. and A. J. Moses, "Problems in the Design of Power Transformers," *IEEE Transactions on Magnetics*, Vol. 10, No. 2, June, 1974, pp. 148–150.
7. Moses, A.J. and B. Thomas. "Comparison of the Localized Power Loss and Flux Distribution in the Butt and Lap and Mitered Overlap Corner Configurations," *IEEE Transactions on Magnetics*, Vol. 10, No. 2, June, 1974, pp. 321–326.
8. Charap, S. and F. Judd. "A Core Loss Model for Laminated Transformers," *IEEE Transactions on Magnetics*, Vol. 10, No. 3, Sept., 1974, pp. 678–681.
9. Nakata, T., N. Takahashi and Y. Kawase. "Magnetic Performance of Step-Lap Joints in Distribution Transformer Cores," *IEEE Transactions on Magnetics*, Vol. 18, No. 6, Nov., 1982, pp. 1055–1057.
10. Basak, A. and P. Caryotis. "Measurement of Loss in Stator Cores Built with Silicon-Iron Laminations Cut at Various Angles to the Rolling Direction," *IEEE Transactions on Magnetics*, Vol. 20, Sept., 1984, pp.1560–1562.
11. Mecrow, B.C. and A. G. Jack. "Modeling of Segmented Laminations in Three-Dimensional Eddy Current Calculations," *IEEE Transactions on Magnetics*, Vol. 28, No. 2, March, 1992, pp. 1122–1125.
12. Ossart, F., E. Hug, O. Huber, C. Buvat and R. Billardon. "Effect of Punching on Electrical Steels: Experimental and Numerical Coupled Analysis," *IEEE Transactions on Magnetics*, Vol. 36, Sept., 2000, pp. 3137–3140.
13. Arshad, W.M., T. Ryckebusch, F. Magnussen, H. Lendenmann, B. Eriksson, J. Soulard and B. Malmros. "Incorporating Lamination Processing and Component Manufacturing in Electrical Machine Design Tools," *Conf. Rec. of 2007 Indus. Appl. Soc. Ann. Mtg.*, Paper # 04P6, 9 pgs.
14. Evans, J.D. and A. L. Von Holle. "Evidence for the Effectiveness of Stress Coatings in Altering Magnetic Properties of Commercially Produced, Grain-Oriented 3% Silicon Iron," *IEEE Transactions on Magnetics*, Vol. 15, No. 6, Nov., 1979, pp. 1580–1585.
15. Moses, A.J. and H. Rahmatizadeh. "Effects of Stress on Iron Loss and Flux Distribution of an Induction Motor Stator Core," *IEEE Transactions on Magnetics*, Vol. 25, No. 5, Sept., 1989, pp. 4003–4005.
16. Arkadan, A.A. and B. W. Kielgas. "Effects of Force Fitting on the Inductance Profile of a Switched Reluctance Motor," *IEEE Transactions on Magnetics*, Vol. 29, No. 2, March, 1993, pp. 2006–2009.
17. Enokizono, M., H. Shimoji and T. Horibe. "Effect of Stator Construction of Three-Phase Induction Motors on Core Loss," *IEEE Transactions on Magnetics*, Vol. 39, No. 3, May, 2003, pp. 1484–1487.
18. Fujisaki, K. and S. Satoh. "Numerical Calculations

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Table II—Calculated Stator Core Loss		
Lamination	Loss	Variation from Original
Original, no segments	840.5 W	-
Type I—Radial-line segment joint	912.4 W	+8.6%
Type II—Half-round segment joint	925.5 W	+10.1%
Type III—Triangle miter segment joint	926.3 W	+10.2%

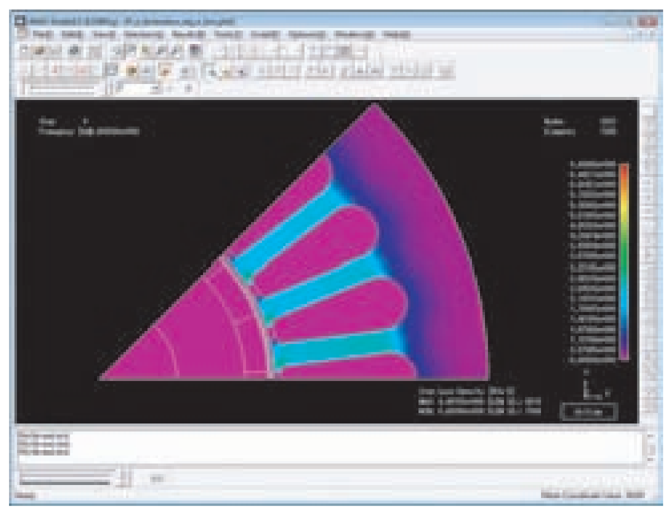

Figure 12—Iron loss density: Original lamination, no segments.

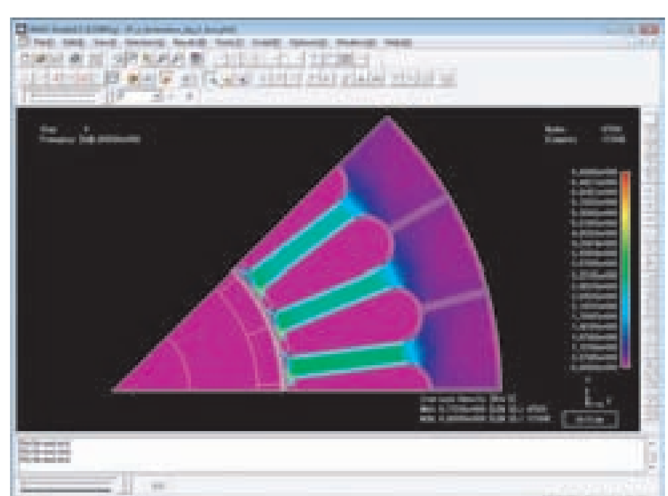

Figure 13—Iron loss density: Type I—Radial-line segment joint.

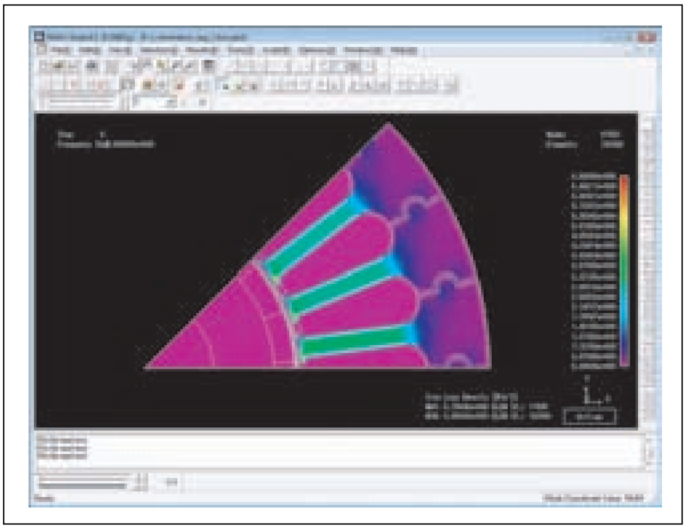

Figure 14—Iron loss density: Type II—Half-round segment joint.

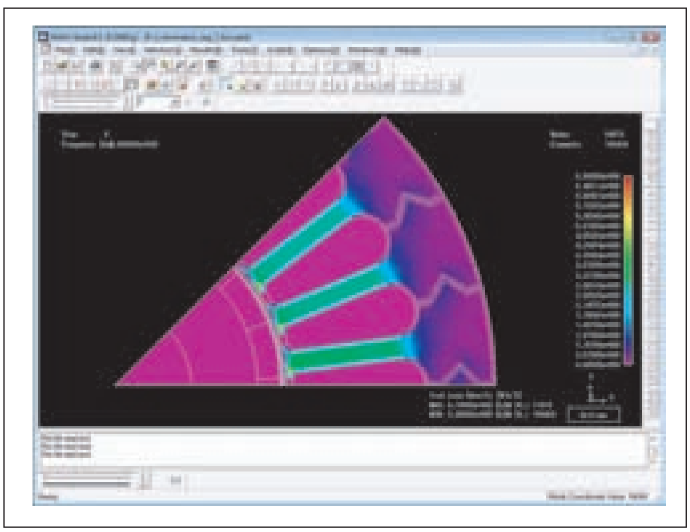

Figure 15—Iron loss density: Type III—Triangle miter segment joint.

of Electromagnetic Fields in Silicon Steel Under Mechanical Stress," *IEEE Transactions on Magnetics*, Vol. 40, No. 4, July, 2004, pp. 1820–1825.

19. Beckley, P. "Electrical Steels for Rotating Machines," Ch. 7, London: IEE, 2002.

20. Tseng, K.-J. and S. B. Wee. "Analysis of Flux Distribution and Core Losses in Interior Permanent Magnet Motor," *IEEE Transactions on Energy Conversion*, Vol. 14, Dec., 1999, pp. 969–975.

21. Boglietti, A, A. Cavagnino, L. Ferraris and M. Lazzari. "The Annealing Influence onto the Magnetic and Energetic Properties in Soft Magnetic Material after Punching," IEEE Conf. Rec of 2003 IEMDC, June 2003, pp. 503 – 508.

22. Chin, Y.-K. and J. Soulard. "Modeling of Iron Losses in Permanent Magnet Synchronous Motors with Field Weakening Capability for Electric Vehicles," *Proc. of the Intl Battery, Hybrid and Fuel Cell Electric Vehicle Symp. & Exhibition*, October, 2002.

23. Slemon, G.R. and X. Liu. "Core Loss in Permanent Magnet Motors," *IEEE Transactions on Magnetics*, Vol. 26, No. 5, Sept., 1990, pp. 1653–1655.

24. Mulder, S.A. "Loss Formulas for Power Ferrites and Their Use in Transformer Design," *Innovation Magnetic*s magazine, Feb., 1994, pp. 1–16.

25. Albach, M., T. Durbaum and A. Brockmeyer. "Calculating Core Losses in Transformers for Arbitrary Magnetizing Currents—A Comparison for Different Approaches," *Proc. of the 2000 IEEE Power Electronics Specialists Conf.*, 2000, pp. 1639–1644.

26. Tan, F., J. Vollin and S. Cuk. "A Practical Approach for Magnetic Core-Loss Characterization," *IEEE Trans. on Power Electronics*, Vol. 10, March, 1995, pp. 124–130.

27. Lavers, J, P. Biringer and H. Hollitecher. "A Simple Method of Estimating the Minor Loop Hysteresis Loss in Thin Laminations," *IEEE Transactions on Magnetics*, Vol. 14, Sept., 1978, pp. 386–388.

28. Di Gerlando, A. and R. Perini. "Evaluation of the Effects of the Voltage Harmonics on the Extra Iron Losses in the Inverter-Fed Electromagnetic Devices," *IEEE Trans on Energy Conversion*, Vol. 14, March, 1999, pp. 57–65.

29. Bertotti, G. "Physical Interpretation of Eddy Currents Losses in Ferromagnetic Materials," *Appl. Phys.*, Vol. 57, No. 6, March, 1985, pp. 2118–2126.

30. Amar, M. and R. Kaczmarek. "A General Formula for Prediction of Iron Losses under Non-sinusoidal Voltage Waveform," *IEEE Transactions on Magnetics*, Vol. 31, No. 5, September, 1995, pp. 2504–2509.

31. Ionel, D.M., M. Popescu, S. J. Dellinger, T.J.E. Miller, R. J. Heideman and M. I. Mc Gilp. "On the Variation with Flux and Frequency of the Core Loss Coefficients in Electrical Machines" *IEEE Transactions on Industry Applications*, Vol. 42, No. 3, May/June, 2006, pp. 658–667.