Journal of the Korean Physical Society, Vol. 40, No. 5, May 2002, pp. 918∼920

Specific Power Loss Comparisons of Magnetic Strips Using Standard Epstein Frame

Hakan KOCKAR*
Science and Literature Faculty, Physic Department, Balikesir University, 10100 Balikesir, Turkey

Turgut MEYDAN
Wolfson Centre for Magnetics Technology, School of Engineering, Cardiff University, U.K.

(Received 24 December 2001, in final form 8 April 2002)

Amorphous magnetic materials are now competing in some of the markets traditionally monopolized by electrical steels. A variety of grain-oriented silicon-iron and amorphous magnetic materials have been under investigation. In order to compare their magnetic properties; we have used an Epstein frame. The samples were magnetized over a range of flux densities from 0.7 T to 1.5 T at 50 Hz. Results show that Metglas 2605SC ($Fe_{81}B_{13.5}Si_{3.5}C_2$) amorphous material is superior to all silicon-iron electrical steels, except for some disadvantages for transformer use.

PACS numbers: 75.60.Ej, 75.50.Bb, 75.50.Kj
Keywords: Power loss, Permeability, Epstein Frame

I. INTRODUCTION

Over the past years, the magnetic properties of commercially produced conventional grain-oriented silicon-iron have improved dramatically, and it has been used as magnetic core material for large rotating machines and transformers. Measurements of the specific power loss and the permeability of magnetic materials result in understanding of the domain structure and show the importance of grain size and orientation, sheet thickness, insulating coating, and stress in silicon-iron [1,2]. This increased understanding of magnetizing processes, combined with better metallurgical control of the steel during the production process, has led to improvements in the properties of the material.

At present, the only commercially available rapidly quenched materials that can substitute the electrical steels are the amorphous magnetic alloys, perhaps the most important soft magnetic materials discovered since ferrites. Amorphous materials have been produced in a composite form in an attempt to compete with conventional silicon-iron for certain applications. Amorphous materials have found even further commercial applications in transducers, sensors, high-frequency devices, electronic power supplies, and magnetic recording heads, replacing a variety of magnetic materials [3-6].

In order to fully understand the basic properties of the magnetic materials an their effects on the performance of devices, it is essential to be able to accurately measure magnetic properties such as the specific power loss and the permeability. The specific power loss of the material is the property that determines the selling price of the product: the lower the specific loss, the higher the price. An internationally accepted standard apparatus for measuring specific power loss of magnetic materials at power frequencies is the Epstein frame [7,8]. In order to compare the magnetic properties of the materials, we measured the specific power losses of various electrical steels, conventional grain-oriented silicon-iron (3 % Si-Fe), laser-scribed grain-oriented 3 % silicon-iron, grain-oriented 6.5 % silicon-iron, and Metglas 2605SC amorphous ribbons by using an Epstein frame. These results are presented in this paper, and the magnetic characteristics of these materials are discussed.

II. EXPERMENTAL PROCEDURE

The Epstein frame with test specimen represents an unloaded transformer whose total losses are measured by using the wattmeter method. Sample strips of materials, 30 cm in length by 3 cm in width, are assembled into a rectangular set of solenoids carrying primary and secondary windings to form a closed magnetic circuit with double overlapped corner joints. The overall thickness of the samples is deliberately kept constant by adjusting number of laminations used in the test for direct comparison. The specific power loss of the test strips is measured for this transformer arrangement operated in a no-load condition in the range of peak flux densities from 0.7 T to

---

*E-mail: hkockar@balikesir.edu.tr; Fax: +90-266-249-3360

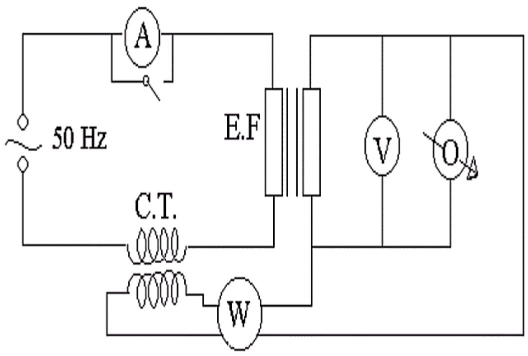

Fig. 1. Schematic diagram of the circuit used for specific power loss measurement (E.F. - Epstein frame, W - wattmeter, V - voltmeter, C.T. - current transformer, O - oscilloscope, A - ammeter).

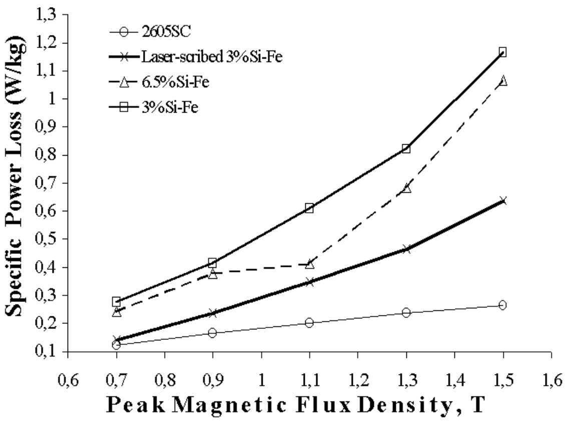

Fig. 2. Variation of the specific power loss with the peak magnetic flux density of the samples measured in the Epstein frame.

1.5 T at 50 Hz. The schematic diagram of the measuring system is presented in Figure 1. The secondary voltage waveform is controlled to be a sinusoidal waveform. Although the corner joint effects on the distribution of the magnetic flux can influence the effective magnetic path length of the Epstein frame and, consequently, the measured value of the specific power loss, for standardization purposes, the effective magnetic path length of the Epstein frame is fixed at 0.94 m, and the declared specific total loss of the test specimen is declared in terms of the performance of the material in the Epstein frame [9].

The primary coil of the Epstein frame used in this investigation energized the magnetic material, and an ammeter was used to monitor the input current. An electrodynamic wattmeter was used to measure the specific power losses. The secondary induced voltage was measured using a high-impedance electronic voltmeter. The magnetic flux density was measured in the stack as a whole and was determined from the secondary coil voltage.

III. RESULTS AND DISCUSION

The measurements of the specific power losses and the magnetic characteristics of the materials were determined by using an Epstein frame. In the following paragraphs, the data from the measurements are presented and discussed.

Users have been calling for better magnetic properties and this has led to the development of so-called domain refined electrical steels. Refinement techniques of scribing and increasing the amount of the silicon content in the material resulted in a lower specific power loss. A number of domain refinement mechanisms for reducing specific power losses of 3 % silicon-iron have been previously proposed [10]. Mechanical scratching perpendicular to the rolling direction at regular intervals on the surface of electrical steel reduces the losses because the beneficial internal stresses are induced. The high internal stress is found not to affect the DC hysteresis loss [10,11].

Figure 2 shows the variation of the specific power loss of the magnetic materials with peak magnetic flux density. Measurements indicate that the lowest specific power loss in this investigation at 50 Hz frequency was achieved in the case of amorphous ribbons. The reason for the amorphous material having the lowest loss is its higher resistivity, thinness and not having any grain boundaries. This would result in superior magnetic properties as compared to electrical steels. The specific power loss values are stacked in merit order with the laser-scribed silicon-iron being the lowest, 6.5 % silicon-iron, and 3 % silicon-iron having higher losses. That means that laser scribing the samples can improve the specific power loss of conventional silicon-iron. Therefore, the specific power loss of laser-scribed 3 % silicon-iron is lower than that of conventional grain-oriented 3 % silicon-iron. However, the scratch depth and the spacing need to be optimized to obtain the best domain refinement. The mechanical scratching technique is difficult to apply commercially, and it damages the surface insulation. An effective technique to produce a scribe pattern is to use a high-power laser beam. The losses of laser-scribed steel are generally 5-8 % lower than those of untreated, high-permeability steel [10]. Specific power losses generally increase smoothly when the peak magnetic flux density is increased, but in Figure 2 for 6.5 % Si-Fe, the increase is not smooth at 1.1 T. The reason for that may be strictly related to the magnetization process, which may be verified by domain observations. Therefore, this deserves further investigation to identify the reason for the deviation of the point of 1.1 T.

Figure 3 shows the peak magnetic flux density versus magnetic field for the grain-oriented 3 % silicon-iron, laser-scribed 3 % silicon-iron, 6.5 % silicon-iron, and an amorphous 2605SC ribbon. The laser-scribed 3 % silicon-iron presented the highest value of permeability,

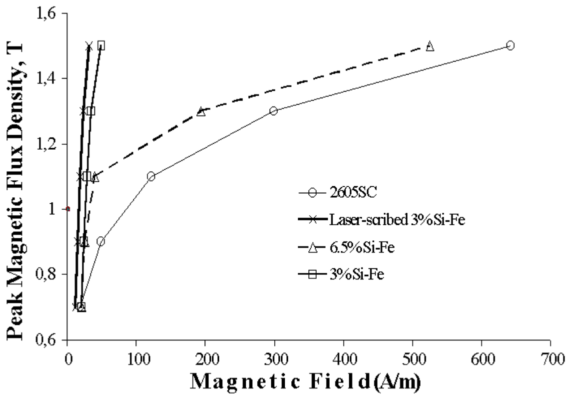

Fig. 3. Variation of the peak magnetic flux density with the magnetizing field in the samples measured in the Epstein frame.

and the amorphous ribbons had the lowest permeability under this specific test. The magnetic characteristics of each sample set varied in a similar manner to the specific power loss, except for the laser-scribed 3 % silicon-iron. The scribing technique causes an increase in the permeability of the silicon-iron. Clarification of the importance of scribing will only be possible once domain observations of the materials have been carried out. Therefore, this deserves further investigation to identify occurrences of higher permeability in laser-scribed materials.

On the other hand, the call for lower loss and higher permeability has led to experimentation on possible chemical additions such as silicon or aluminium in electrical steels. If the eddy-current component of loss is to be reduced, high silicon content is needed, although manganese shows potential for development [12,13]. In this study, an increase in the silicon content (from 3 % silicon to 6.5 % silicon in electrical steel) resulted in a decrease in the specific power losses of the electrical steel, as indicated in Figure 2. However, the higher the silicon content, the lower the permeability, as can be seen in Figure 3. Although silicon can reduce the coercive force and increase the resistivity, present trends are mainly toward lower additives and cleaner steels to keep induction high and losses low [14].

Furthermore, despite the superior properties of amorphous ribbons, the thickness limitation on amorphous ribbons is a disadvantage. There has been much research [15-17], however, showing that it might be possible to eliminate this limitation in time. The material is, however, still too brittle as a replacement material for commercial silicon-iron for transformer applications.

IV. CONCLUSIONS

A comparative study of various magnetic materials was undertaken. Results indicate that amorphous materials outperformed all other materials in terms of specific power losses. The next best performer was laser-scribed silicon-iron, followed by 6.5 % silicon-iron, and finally 3 % silicon-iron. As researchers gain better understanding of materials, it is likely that these two types of the materials will be improved and more widely used in industrial applications. Furthermore, it is essential that the development of new materials go hand in hand with a better understanding of their operational requirements in devices. The effects of core geometry and normal flux on losses and magnetizing conditions should be better understood to enable tomorrow's materials to be used to their full potential in electromagnetic devices.

ACKNOWLEDGMENTS

H. Kockar is grateful to Wolfson Centre, Cardiff University, UK, for support and help during the experimental work. Balikesir University, Temel Bilimler, Arastirma ve Uygulama Merkezi (BUTAM), Turkey, is also gratefully acknowledged for support.

REFERENCES

[1] J. Sievert, J. Magn. Magn. Mater. **215**, 647 (2000).
[2] J. Sievert, H. Ahlers, M. Birkfeld, B. Cornut, F. Fiorillo, K. A. Hempel, T. Kochmann, A. KedousLebouc, T. Meydan, A. Moses and A. M. Rietto, J. Magn. Magn. Mater. **160**, 115 (1996).
[3] C. K. Kim, I. H. Lee, Y. C. Chung and R. C. O'Handley, Mat. Sci. Eng. B - Solid **76**, 211 (2000).
[4] S. K. Zhou, J. Mater. Sci. Technol. **16**, 131 (2000).
[5] A. Moldovanu, H. Chiriac, C. Moldovanu, M. Macoviciuc and C. Ioan, Sensors Actuators A - Phys. **81**, 189 (2000).
[6] F. Jerems, C. Mac Mahon, A. G. Jenner and R. D. Greenough, Ferroelectrics **228**, 333 (1999).
[7] R. Kaczmarek, M. Amar and F. Protat, IEEE Trans. Magn. **32**, 189 (1996).
[8] R. K. Kotnala and P. C. Kothari, Indian J. Pure Appl. Phys. **38**, 797 (2000).
[9] BS 6404, British Standards Institution, Part 2, 4 (1985).
[10] A. J. Moses, *IEEE Proceedings* (New York, Sept., 1990), Vol. 137, p. 233.
[11] O. S. Anilturk and A. R. Koymen, J. Magn. Magn. Mater. **213**, 281 (2000).
[12] Y. H. Han, J. J. Suh, M. S. Shin and S. K. Han, J. Physics-IV **7** (C1), 111 (1997).
[13] J. J. Suh, B. M. Song and Y. H. Han, IEEE Trans. Magn. **36**, 3402 (2000).
[14] L. Sheiko, A. Moroshkin, S. Gaiduk, J. Magn. Magn. Mater. **158**, 457 (1996).
[15] A. Y. Rojeab, W. Hosny, Elect. Pow Comp. Sys. **29**, 555 (2001).
[16] H. Chiriac, N. Lupu, Physica B **299**, 293 (2001).
[17] F. T. Parker, F. E. Spada, A. E. Berkowitz, K. S. Vecchio, E. J. Lavernia and R. Rodriguez, Mater. Lett. **48**, 184 (2001).