

Influence of Manufacturing Process on Core Losses of Electric Machines

Shiwei Zhang¹, Chengcheng Liu¹, *Member, IEEE*, Gang Lei², *Senior Member, IEEE*, and Jianguo Zhu³, *Senior Member, IEEE*

¹State Key Laboratory for Reliability and Intelligence of Electrical Equipment, Hebei University of Technology, Tianjin, 300130, China, 985646120@qq.com, 2016020@hebut.edu.cn.

²School of Electrical and Data Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia, gang.lei@uts.edu.au.

³School of Electrical and Information Engineering, University of Sydney, Sydney, NSW 2006, Australia, jianguo.zhu@sydney.edu.au.

Iron loss is a key factor in machine performance and energy efficiency design. Amorphous alloy (AA) materials are increasingly being widely used in machine design to improve efficiency due to their excellent magnetic properties such as high permeability and low iron loss. However, the magnetic properties of AA can be significantly affected during the manufacturing process, which may lead to magnetic degradation of the material, resulting in a large deviation between predicted and measured iron losses at the machine design stage. Therefore, magnetic property measurement experiments are carried out to investigate the effect of the manufacturing process on the magnetic properties of AA and non-grain-oriented silicon steel (NGO) in this paper. Meanwhile, the iron loss model is improved on this basis, which more accurately reflects the influence of the manufacturing process. Moreover, a finite element model of a permanent magnet synchronous machine (PMSM) is developed to analyze the effect of the manufacturing process on the performance of PMSM. Finally, two prototypes with different stator cores are fabricated and experimentally tested to verify the effectiveness of the above method.

Index Terms—iron loss, amorphous alloy (AA), manufacturing process, permanent magnet synchronous machine (PMSM).

I. INTRODUCTION

THE core loss is one of the main energy losses in machine operation, and its size directly affects the efficiency, temperature rise and performance stability of the machine. In recent years, amorphous alloys (AA) have received more and more attention in the field of machine design due to their low loss, high saturation magnetic induction strength, and excellent soft magnetic properties [1]. However, while the AA offers significant core loss advantages over conventional non-grain-oriented silicon steel (NGO), their performance is significantly affected by the manufacturing process. For example, stamping, laser cutting, welding, interlocking, and other processing methods can lead to degradation of the magnetic properties, which can increase iron losses [2].

Traditional core loss models do not take into account the influence of the magnetic properties of the material by the manufacturing process, which makes it difficult to accurately reflect the actual core loss characteristics. To address this issue, the improved loss model was adopted to consider the effect of the manufacturing process on core loss [3]. Moreover, the effect of the manufacturing process on the magnetic properties of NGO was measured experimentally, and the experimental test data were combined with finite element analysis to improve the accuracy of core loss predictions. However, the influence of the manufacturing process on the magnetic properties of AA material has been presented in very few relevant studies. Therefore, it is particularly important to conduct a quantitative study of the manufacturing process for its magnetic properties and core loss characteristics.

In this paper, an improved core loss model is proposed by experimental measurements for the change of magnetic

properties of AA and NGO materials under different manufacturing processes. To evaluate the above proposed core loss model, a permanent magnet synchronous machine (PMSM) was employed and simulated. Finally, a prototype was fabricated and the accuracy of the core loss model was verified experimentally. The results of the study confirm the potential of AA materials in reducing core losses and reveal the significant influence of the fabrication process on the core losses of the machine.

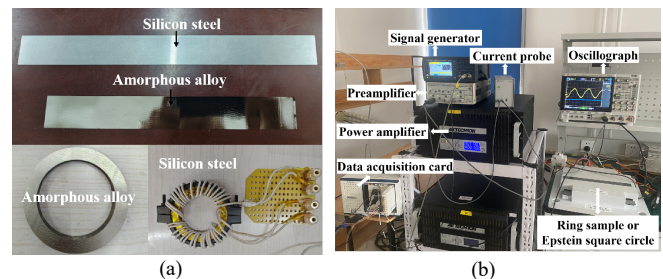


Fig. 1. Measurement of magnetic properties, (a) samples of AA and NGO, (b) the experimental platform.

II. MEASUREMENT OF MAGNETIC PROPERTIES AND IMPROVED CORE LOSS MODEL

A. Comparison of magnetic properties

Fig. 1(a) shows the stacked sheets and ring samples of NGO and AA, and the ring samples are treated by processes such as wire cutting and bonding. The magnetic properties are measured based on the Epstein frame and toroidal sample methods, respectively, and the test platform is shown in Fig. 1(b). Fig. 2(a) shows the magnetization curves for the above materials, it can be seen that the permeability of both AA and NGO materials is reduced after the manufacturing process compared to the original data tested using Epstein frame.

Meanwhile, the core loss of AA is lower than that of NGO at the same magnetic density and frequency. Moreover, the core losses of both materials are increased after the fabrication process as shown in Fig. 2(b). Therefore, the use of the original magnetic characteristics will cause large errors in the design of the machine, and further improvements in the core loss model are required. In addition, the reasonable use of AA can enhance the performance of machine.

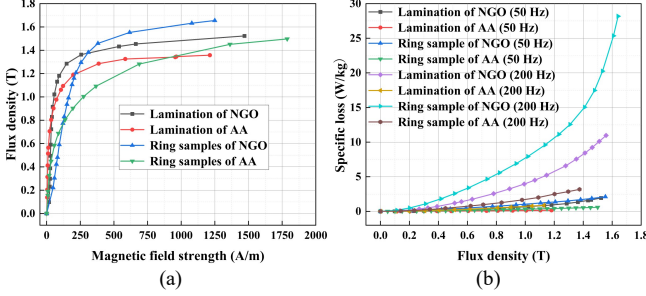


Fig. 2. Magnetic properties of NGO and AA material, (a) magnetization curves, (b) core loss curves.

B. Improved core loss model considering the manufacturing process

Traditionally core losses are calculated using a standard Epstein frame measurement test setup and these core losses are denoted as P_{core} in this paper. Meanwhile, the manufacturing effect is not considered in P_{core} . The three components core loss equation (1) was applied for the calculation of core loss.

$$P_{core} = \sum_{v=1}^N k_h B^\alpha v f + k_e B^2 (v f)^2 + k_a B^{1.5} (v f)^{1.5} \quad (1)$$

where k_h , k_e , and k_a are hysteresis, eddy current, and additional loss coefficients of the non-degraded material, α is empirical parameter, f is the frequency, B is the flux density, and v is the number of harmonics.

The effect of wire cutting and bonding on core losses is expressed in the coefficient $k_{process}(B, f)$, which represents the relative percentage increase in core losses. The polynomials with respect to flux density and frequency are fitted to calculate the coefficient $k_{process}(B, f)$, whose values are derived from the core loss test results in Fig. 2(b). The density of core loss P with manufacturing effects is presented by equation (2).

$$P = (1 + k_{process}(B, f)) P_{core} \quad (2)$$

III. SIMULATION CALCULATION AND EXPERIMENTAL VERIFICATION

A. Introduction of manufacturing effects in FEM

Fig. 3(a) shows the model of the PMSM with the same rotor core while the stator core is made of NGO or AA material. Meanwhile, the FEM simulation calculation is performed for both machines. To take the manufacturing effect into account in the calculation of core losses, the magnetic flux density and volume in each mesh cell of the finite element are first calculated and then brought into Eq. (2) to calculate the core losses of PMSM. Fig. 3(b) shows the comparison of the calculated core losses and it can be seen that the core losses using the improved core loss model have increased compared

to the core losses using the existing model, which is more in line with the reality of the machine after manufacturing and processing. Moreover, the use of AA materials for stator cores can significantly reduce the core losses of machines.

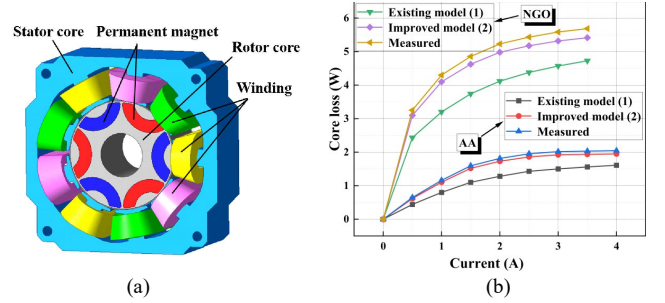


Fig. 3. (a) The model of PMSM, (b) comparison of core loss.

B. Experimental results

Fig. 4(a) shows the stator core of PMSM, whose manufacturing process is consistent with the ring sample. Fig. 4(b) and (c) show the rotor core and the adopted PMSM prototype, respectively. Fig. 4(d) shows the test platform of the experiment, where the performance of the machine in terms of iron loss, no-load electromotive force, torque, and efficiency is tested. The validity of the improved core loss model and simulation design is verified through core loss test results shown in Fig. 3(b).

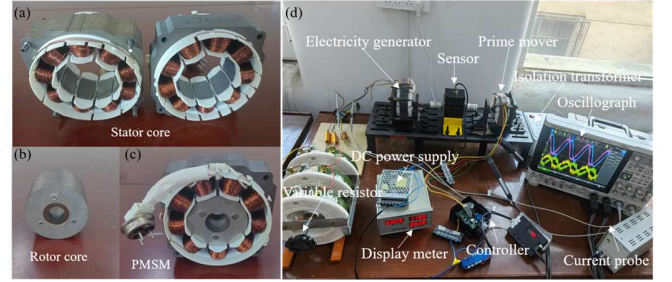


Fig. 4. Experimental platform.

IV. CONCLUSION

In this paper, the magnetic properties of AA and NGO under different manufacturing processes are measured to illustrate the degradation of magnetic properties of materials in this process. Meanwhile, an improved iron loss model is proposed and combined with the finite element tool to achieve an accurate calculation of core loss. Finally, an experimental validation was carried out. The results show that AA materials can significantly reduce core losses in machine design, and the improved core loss model enhances the accuracy of core loss prediction.

REFERENCES

- [1] B. Li, J. G. Zhu, C. Liu, Y. Li, F. Zhao and Q. Jiang, "Design and Comparative Study of Ultrahigh-Speed Permanent Magnet Motors with Different Soft Magnetic Materials," *IEEE Trans. Mag.*, vol. 59, no. 11, pp. 1-5, Nov. 2023.
- [2] N. Boubaker, D. Matt, P. Enrici, F. Nierlich and G. Durand, "Measurements of Iron Loss in PMSM Stator Cores Based on CoFe and SiFe Lamination Sheets and Stemmed from Different Manufacturing Processes," *IEEE Trans. Mag.*, vol. 55, no. 1, pp. 1-9, Jan. 2019.
- [3] M. Bali and A. Muetze, "Modeling the Effect of Cutting on the Magnetic Properties of Electrical Steel Sheets," *IEEE Trans. Ind. Electron.*, vol. 64, no. 3, pp. 2547-2556, March 2017.