Article:

Zhu, Z.Q., Xia, Z.P., Atallah, K. et al. (2 more authors) (2000) Powder alignment system for anisotropic bonded NdFeB Halbach cylinders. IEEE Transactions on Magnetics, 36 (5). pp. 3349-3352. ISSN 0018-9464

https://doi.org/10.1109/20.908796

Powder Alignment System for Anisotropic Bonded NdFeB Halbach Cylinders

Z. Q. Zhu, *Member, IEEE*, Z. P. Xia, K. Atallah, G. W. Jewell, and D. Howe

***Abstract*—A Halbach cylinder, fabricated from pre-magnetized sintered NdFeB magnet segments, is proposed for the powder aligning system during the compression or injection moulding of anisotropic bonded Halbach oriented NdFeB ring magnets. The influence of leading design parameters of the powder aligning system, *viz*. the number of magnet segments per pole, their axial length and radial thickness, and their clearance from the mould, is investigated by finite element analysis, and validated experimentally.**

***Index Terms*—Bonded NdFeB, Halbach magnetization, permanent magnet, powder alignment.**

I. Introduction

GENERALLY, Halbach cylinders [1] are fabricated either from pre-magnetized anisotropic magnet segments having magnetization orientations which approximate the Halbach field distribution [2], or moulded as bonded isotropic ring magnets which are subsequently impulse magnetized by a sinusoidally distributed magnetizing field [3]. In order to enhance the performance of bonded Halbach cylinders, it is possible to employ an anisotropic moulding compound which can be oriented during the compression or injection moulding process to produce an anisotropic bonded Halbach cylinder. Thus, the magnet powder is both oriented and subsequently impulse magnetized by a sinusoidally distributed field. However, whilst the required aligning field for anisotropic NdFeB powder is <1 T, the required magnetizing field is >3 T. This paper describes the design of a permanent magnet powder aligning system, which is used to orient an HDDR-derived NdFeB moulding compound, grade NDA-502E, during the injection moulding of an anisotropic bonded Halbach oriented ring magnet. The influence of leading design parameters is investigated by finite element analysis, the findings being validated experimentally.

II. 2-D Analysis of Powder Alignment System

Although the aligning field could be produced by an appropriately designed electromagnet, a permanent magnet aligning fixture is preferred since it does not require a power supply. Thus, a Halbach cylinder aligning fixture was fabricated from pre-magnetized sintered NdFeB magnet segments.

Manuscript received February 14, 2000. This work was supported by the UK Engineering and Physical Sciences Research Council, under Grant GR/L 76471.

The authors are with the Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, S1 3JD, UK (e-mail: Z.Q.Zhu@sheffield.ac.uk).

Publisher Item Identifier S 0018-9464(00)08237-6.

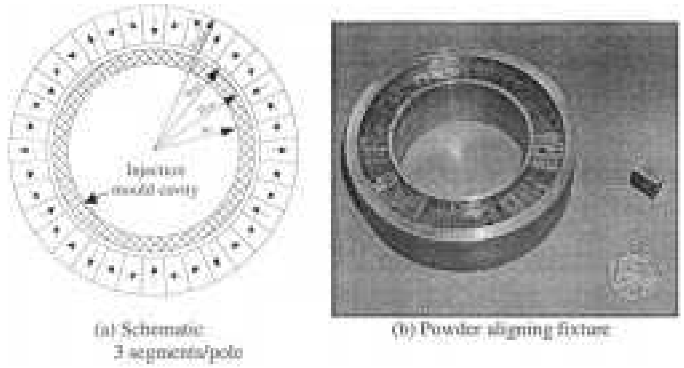

Fig. 1. 12-pole sintered NdFeB Halbach powder aligning system. (a) Schematic 3 segments/pole. (b) Powder aligning fixture.

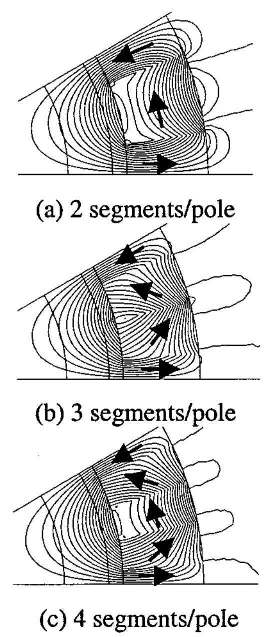

Fig. 2. Field distribution in segmented Halbach aligning system. (a) 2 segments/pole. (b) 3 segments/pole. (c) 4 segments/pole.

Fig. 1 shows the 12-pole powder aligning system. It employs 3 magnet segments per pole, the inner and outer radii, R_{a1}, and R_{a2}, being 29 mm and 39 mm, respectively. The system has been used to orient an injection moulded NdFeB magnet having an axial length of 14 mm, and inner and outer radii of $R_r = 17$ mm and $R_m = 27$ mm, respectively.

Fig. 2 shows the influence of the number of segments per pole, *viz*. 2, 3, and 4, on the aligning field distribution, while Fig. 3 shows the corresponding field distributions at R_{a1}, R_m and R_r, respectively. As will be seen, both the radial and

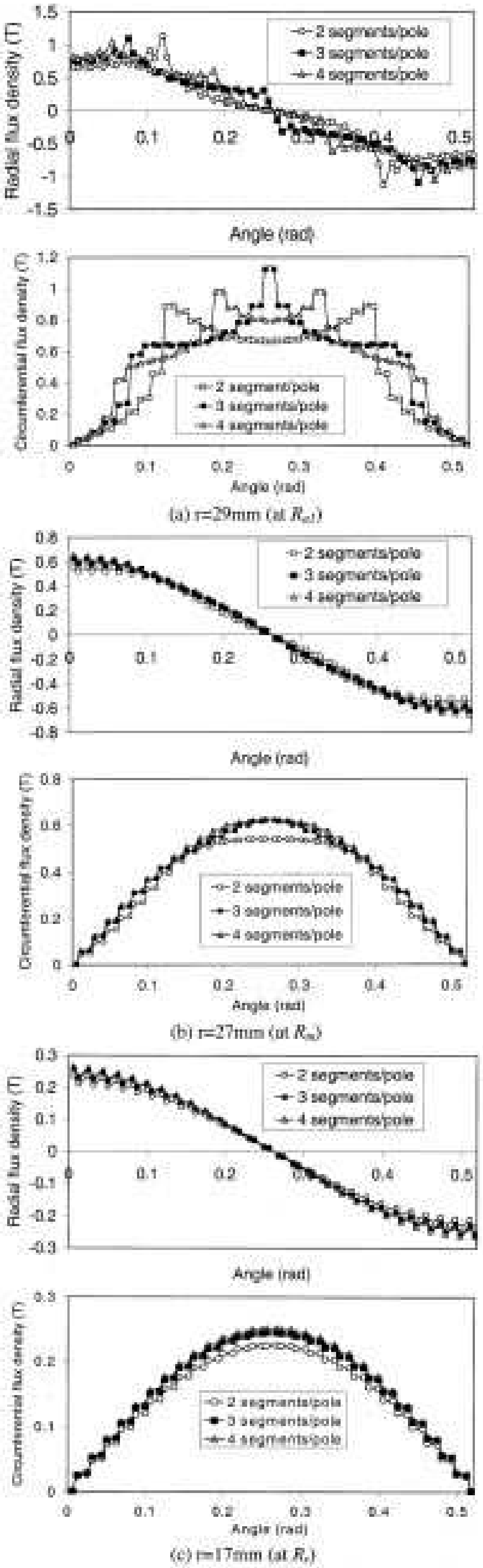

Fig. 3. Flux density distribution at different radii. (a) $r = 29$ mm (at R_{a1}). (b) $r = 27$ mm (at R_m). (c) $r = 17$ mm (at R_r).

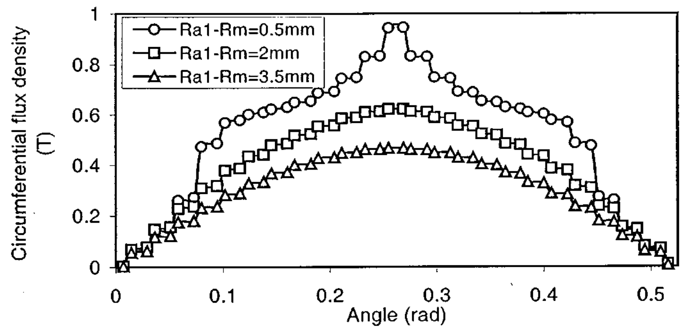

Fig. 4. Flux density distribution at $R_m = 27$ mm for different clearances between mould cavity and powder aligning magnet, $R_{a1} = 29$ mm, $R_{a2} = 39$ mm.

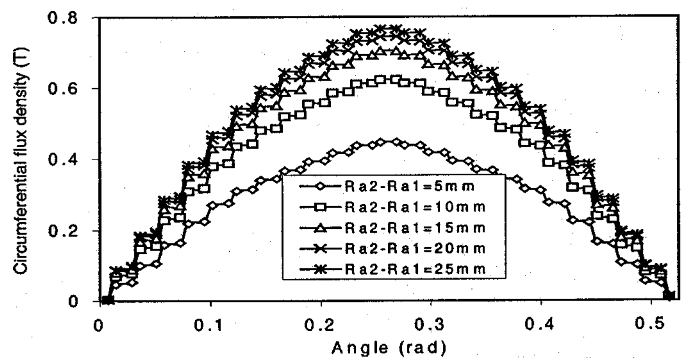

Fig. 5. Flux density distribution at $R_m = 27$ mm for different radial thicknesses of powder aligning magnet. ($R_{a1} - R_m = 2$ mm).

circumferential components of flux density exhibit significant harmonics close to the bore of the aligning system. However, these decay quickly with radius, and the field distributions at the inner and outer surfaces of the mould cavity are essentially sinusoidal. Although the use of a higher number of segments per pole improves the field distribution, it generally increases the cost. Therefore, 3 segments per pole were deemed to be appropriate. However, Fig. 2 clearly shows that the clearance, $(R_{a1} - R_m)$, between the mould cavity and the bore of the powder aligning magnet has a significant influence on both the amplitude and waveform of the aligning field. Fig. 4 shows the distribution of the circumferential component of the aligning field at R_m for three different clearances. As can be seen, there is an optimum clearance, in terms of maximizing the amplitude of the aligning field whilst minimizing the harmonic content, which arises from the segmented approximation of the aligning Halbach cylinder. A clearance, $(R_{a1} - R_m)$, of 2 mm, which was selected, since this was compatible with the required wall thickness of the mould.

Fig. 5 shows the influence of the radial thickness, $(R_{a2} - R_{a1})$, of the Halbach cylinder on the circumferential component of the aligning field. As can be seen, while the amplitude of the aligning field increases as R_{a2} is increased, there is a diminishing return when $(R_{a2} - R_{a1}) > 10$ mm. Although, a field of ≈0.6 T is required to fully orient the NdFeB compound, in practice this cannot be achieved throughout the entire volume of the mould cavity. However, the influence of partial alignment of the powder on the subsequent performance of the injection moulded magnet can be calculated [4].

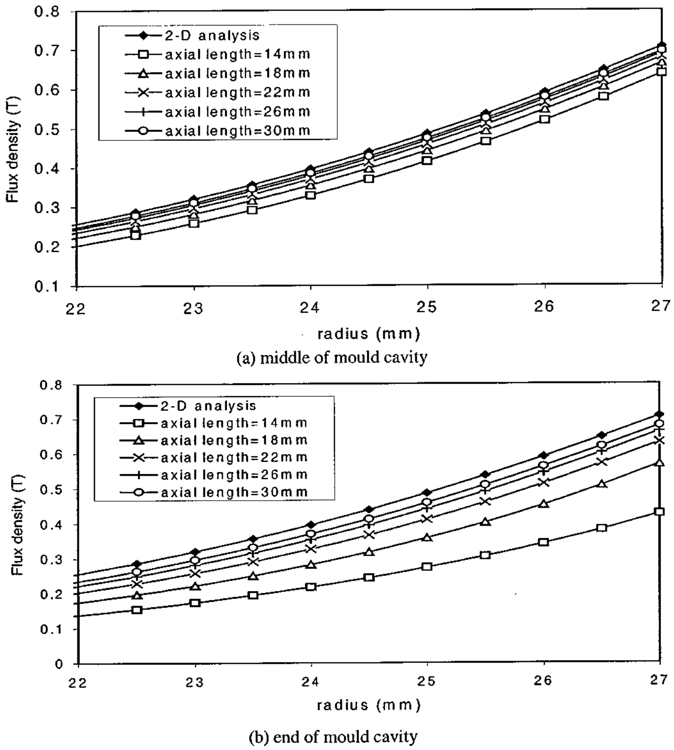

Fig. 6. Variation of flux density with axial length of aligning system. (a) Middle of mould cavity. (b) End of mould cavity.

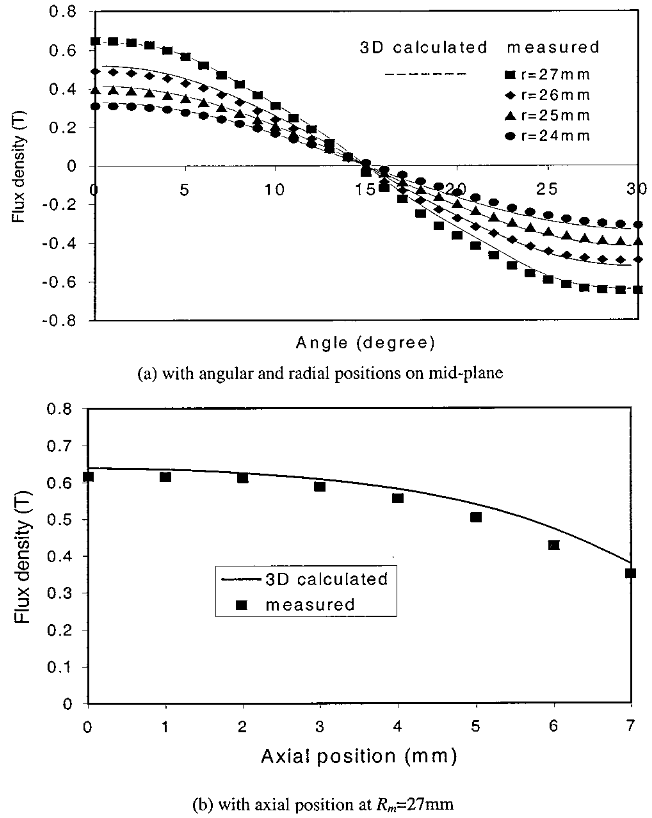

Fig. 7. Measured and predicted variation of radial flux density. (Axial length of aligning system = 14 mm). (a) with angular and radial positions on mid-plane. (b) With axial position at $R_m = 27$ mm.

III. 3-D Analysis of Powder Alignment System and Experimental Validation

The foregoing results were deduced from 2-d finite element analyzes. However, since the proposed Halbach powder aligning system is ironless, the end-effects may be significant. Therefore, the system performance was also predicted by 3-d finite element analysis. The predicted variation of flux density with radius at the middle and end of the mould cavity, together with the flux density predicted earlier from 2-d analysis, is shown in Fig. 6. The 3-d analyzes show that there is a significant reduction in the flux density, especially at the end of the mould and that a significant axial field component exists around the ends of the aligning magnet. In order to improve the uniformity of the field along the axial length of the mould cavity, therefore, the powder aligning magnet must be axially longer than the mould cavity. In order to assess the extent of the end-effect and its dependence on the axial length of the aligning magnet, 2-d and 3-d finite element analyzes were undertaken as the axial length was varied from 14 mm to 30 mm, in 4 mm increments, the axial length of the mould cavity being 14 mm, as before, with $R_{a1} - R_m = 2$ mm and $R_{a2} - R_{a1} = 10$ mm. The ratio of the 2-d and 3-d calculated peak flux densities at the ends of the mould varied from 0.6 for 14 mm axial length to 0.97 for 30 mm axial length. Figs. 7 and 8 compare the measured and 3-d finite element predicted variation of the radial component of the aligning field distribution when the axial length of the aligning system is 14 mm and 30 mm, respectively. As can be seen, good agreement is achieved.

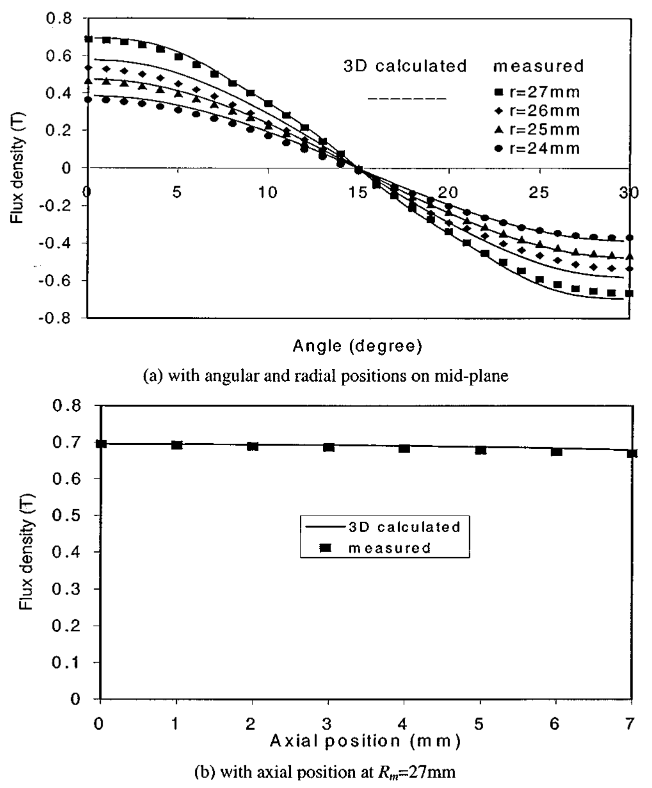

Fig. 8. Measured and predicted variation of radial flux density. (Axial length of aligning system = 30 mm). (a) With angular and radial positions on mid-plane. (b) With axial position at $R_m = 27$ mm.

IV. Conclusion

2-d and 3-d finite element analyzes have been used to investigate the influence of various design parameters on the performance of a permanent magnet powder aligning system for the injection moulding Halbach oriented, bonded anisotropic NdFeB ring magnets. It has been shown that an appropriately proportioned Halbach system, comprising a small number of sintered NdFeB magnets per pole, is suitable. In order to achieve the required uniformity of field within the mould cavity, the axial length of the powder aligning system must be longer than that of the cavity.

References

[1] K. Halbach, "Design of permanent magnet multipole magnets with oriented rare earth cobalt material," *Nuclear Instrum. Methods*, vol. 169, pp. 1–10, 1980.

[2] M. Marinescu and N. Marinescu, "New concept of permanent magnet excitation for electrical machines—analytical and numerical computation," *IEEE Trans. Magn.*, vol. 28, pp. 1390–1393, 1992.

[3] K. Atallah and D. Howe, "The application of Halbach cylinders to brushless ac servo motors," *IEEE Trans. Magn.*, vol. 34, pp. 2060–2062, 1998.

[4] Z. Q. Zhu, Z. P. Xia, K. Atallah, J. W. Jewell, and D. Howe, "Analytical modeling of multipole anisotropic bonded NdFeB magnet Halbach cylinders accounting for partial powder alignment," in *Proc. InterMag 2000*, paper DQ-09.