JOURNAL OF APPLIED PHYSICS **109**, 07A743 (2011)

High performance bonded neo magnets using high density compaction

J. Herchenroeder,[1,a)] D. Miller,[2] N. K. Sheth,[2] M. C. Foo,[2] and K. Nagarathnam[3]
[1]*Magnequench International, Pendleton, Indiana 46064, USA*
[2]*Magnequench Technical Centre, 117525, Singapore*
[3]*Utron Kinetics, LLC, Manassas, Virginia 20110, USA*

(Presented 18 November 2010; received 13 October 2010; accepted 21 December 2010; published online 11 April 2011)

This paper presents a manufacturing method called Combustion Driven Compaction (CDC) for the manufacture of isotropic bonded NdFeB magnets (bonded Neo). Magnets produced by the CDC method have density up to 6.5 g/cm^3 which is 7–10% higher compared to commercially available bonded Neo magnets of the same shape. The performance of an actual seat motor with a representative CDC ring magnet is presented and compared with the seat motor performance with both commercial isotropic bonded Neo and anisotropic NdFeB rings of the same geometry. The comparisons are made at both room and elevated temperatures. The airgap flux for the magnet produced by the proposed method is 6% more compared to the commercial isotropic bonded Neo magnet. After exposure to high temperature due to the superior thermal aging stability of isotropic NdFeB powders the motor performance with this material is comparable to the motor performance with an anisotropic NdFeB magnet. © *2011 American Institute of Physics*. [doi:10.1063/1.3565194]

I. INTRODUCTION

Bonded Neo magnets based on isotropic NdFeB powder such as Magnequench MQP^{TM} provide a maximum energy product of 8–10 MGOe significantly better than a typical value of 4 MGOe for ferrite magnets but lower than 40 MGOe provided by sintered neo magnets. There are applications in automobiles, pumps, power tools, and consumer electronics where a magnet with $(BH)_{max}$ of 11–12 MGOe would enable the next generation of compact, lighter weight, and electrically efficient products.

A compression bonded Neo magnet is comprised of NdFeB powder, epoxy, and additives conducive to magnet manufacture such as curing agents, coupling agents and lubricants.[1–3] After compaction, typical magnet densities are 5.8–6.1 g/cm^3. However the theoretical density of a compound of magnetic powder and organic binders can reach 6.9 g/cm^3 indicating that higher $(BH)_{max}$ can be obtained if density were increased during molding.

Increasing the density of the magnet may be acheived by reducing the percentage of the epoxy binder or by increasing the compaction pressure.

Utron Kinetics has developed an innovative approach to powder compaction called Combustion Driven Compaction (CDC). CDC has been successfully shown to compact metals, ceramics, magnetic materials, and composites up to 23 tonne/cm^2.[4–7] Unlike explosive compaction,[8,9] CDC involves smooth, gradually raising, continuous pressure loading which minimizes the tendency for cracking and does not require a ductile metal containment sleeve facilitating manufacture of net shape magnets.

II. COMBUSTION DRIVEN COMPACTION METHOD

In conventional compression molding (CCM) an upper punch driven by a mechanical or hydraulic ram provides the pressure used to consolidate the powder into a final shape, and then the bottom punch is used to eject the part. Because of strength limitations of the tooling and the friction encountered during ejection, compaction pressure is limited to about 7 to 11 tonne/cm^2 and a density range of 5.8–6.1 g/cm^3. In such magnets, $(BH)_{max}$ is limited to 9 MGOe for the lower pressure and 10 MGOe for the higher pressure.

The CDC method[4,7] utilizes controlled high pressure combustion of methane (natural gas) and air to produce higher compaction pressures. Figure 1(a) shows the schematic diagram for CDC method while the actual CDC press is shown in Fig. 1(b). In operation a combustible gas mixture is fed into the combustion chamber which is sized to deliver a set force to the upper punch ram at a defined chamber

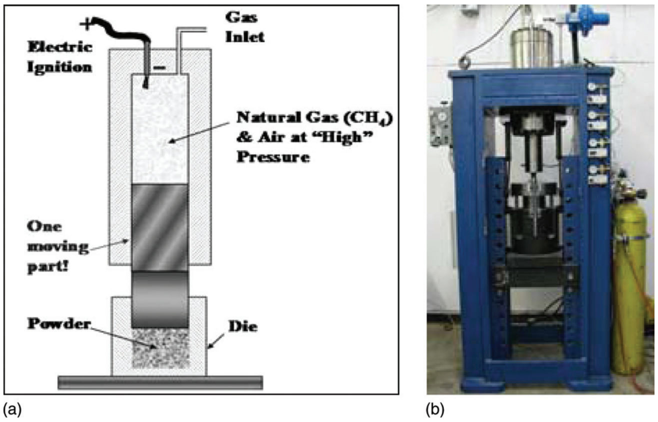

FIG. 1. (Color online) (a) Schematic of CDC process. (b) 360 tonne CDC press.

---

[a] Electronic mail: jwh@magnequench.com.

TABLE I. Test results of $\varphi 15 \times 13$ mm cylindrical magnets. The data are an average of 4 magnets ± one standard deviation. Die cracking and part delamination can be controlled by careful control of pressing parameters.

Pressure tonne/cm^2	Density g/cm^3	$(BH)_{max}$ MGOe	H_{ci} kOe
12	6.12 ± 0.015	10.4 ± 0.04	8.9 ± 0.03
21	6.37 ± 0.012	11.6 ± 0.04	9.1 ± 0.01

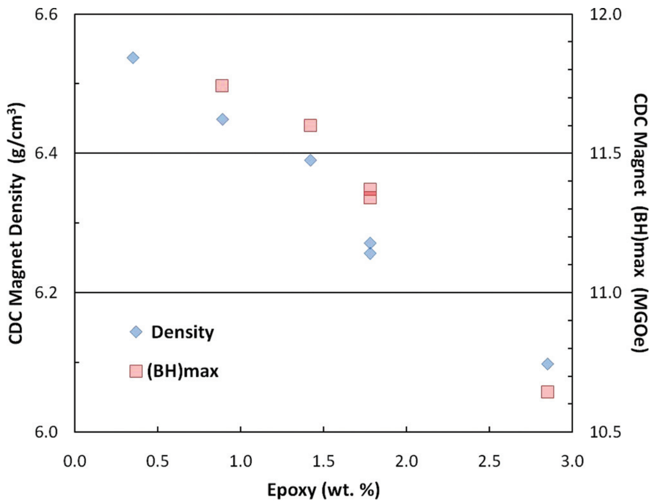

FIG. 2. (Color online) Effect of epoxy on properties of cylinder CDC magnet.

TABLE II. Properties of isotropic bonded rings. The energy product and remanence are estimated from the magnetic properties of MQP-B+^{TM} powder and the magnet density.

	Density g/cm^3	$(BH)_{max}$ MGOe	B_r kG
CCM	5.88	9.5	6.8
CDC	6.22	10.6	7.2

TABLE III. Back-emf constant of motor for different magnets. The indicated range is ± one standard deviation.

Type of Magnet		
Anisotropic Neo	Isotropic Neo using CCM	Isotropic Neo using CDC
	k_b (mV/rpm) before thermal aging	
4.52 ± 0.02	3.98 ± 0.04	4.25 ± 0.03
	k_b (mV/rpm) after thermal aging	
4.40 ± 0.05	3.93 ± 0.05	4.16 ± 0.03

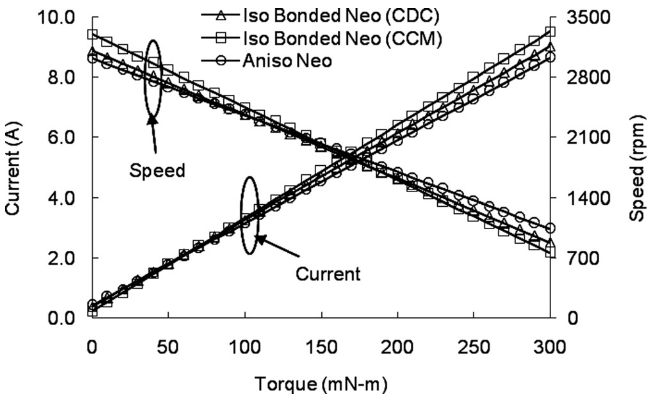

FIG. 3. Variation of speed and current of seat motor before thermal aging.

pressure. Pressure can be adjusted after tool construction by controlling the gas mixture ratios in the case of combustion.

The CDC process was successfully applied to a simple cylinder geometry of diameter 15 mm and length 13 mm using MQLP-B^{TM} powder from Magnequench and curing conditions between 150 and 225 °C for 1 h in argon gas. MQLP-B is MQP-B^{TM} magnet powder precoated with 1.6% epoxy. Table I illustrates these results.

The density and magnetic properties achieved at CDC compaction pressure of 12 tonne/cm^2 are equivalent to the best bonded Neo magnets commercially available. The magnetic properties of the 21 tonne/cm^2 magnets are at a level significantly higher than commercially available magnets and would be welcomed by magnet users.

In a second study on the same cylinder magnet, the amount of epoxy was varied. In this case, MQP-B was mixed with a powdered epoxy, and the mixture was compacted at 20 tonne/cm^2 on average. Figure 2 shows that density can be increased as the amount of epoxy is lessened and that the energy product follows the same trend in CDC compacted magnets.

III. EFFECT OF DIFFERENT MAGNETS ON SEAT MOTOR PERFORMANCE

Using the CDC method,[2] ring magnets with 33.7 mm outside diameter, 1.5 mm wall thickness, and 25.3 mm length were produced. The CDC magnets were made from MQLP-B+^{TM} powder with 1% epoxy, compacted with an

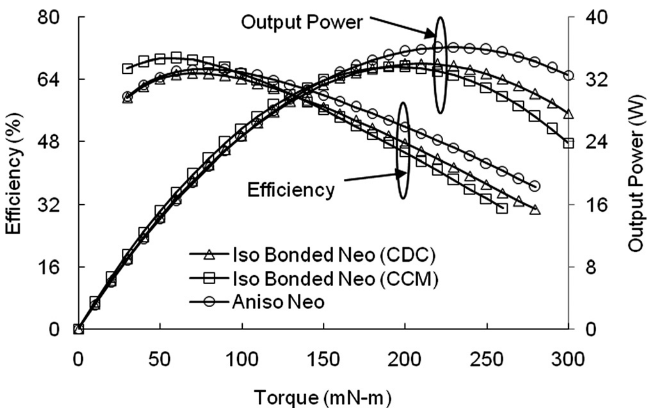

FIG. 4. Variation of efficiency and output power of seat motor before thermal aging.

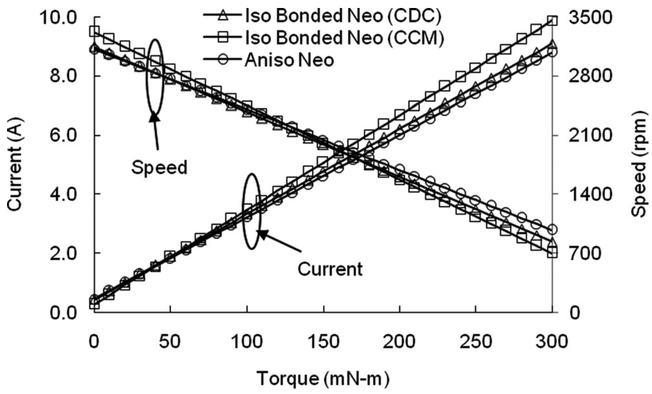

FIG. 5. Variation of speed and current of seat motor after thermal aging.

average of 20 tonne/cm^2 pressure and cured at 160 °C for 1 h in argon gas. The dimensions are the same as those for an anisotropic bonded Neo magnet found in a commercially available seat motor. Additionally, traditional isotropic bonded magnets of the same size produced by CCM were sourced from the market to compare the performance of the magnets produced by CDC and CCM. The density of both types of isotropic magnets was measured using the water displacement method, and magnetic properties were estimated based on the magnet density and epoxy content. The results for a magnet from each CDC and CCM used in the subsequent motor analysis are in Table II. The magnet produced by CDC exhibits 5.8% higher density compared to the magnet produced using CCM.

Both the magnets were magnetized to saturation with four-pole radial orientation using the same magnetizing fixture. The magnets were assembled into the seat motor and the back-emf constant (k_b) of the motors was measured at 1350 rpm for both the isotropic and anisotropic magnets.

Table III gives the back-emf constant of the motor with different magnets. From Table III it is observed that the motor with the anisotropic Neo magnet has 11.9% higher back-emf constant compared to the isotropic magnet produced by CCM, but the use of isotropic magnet produced by CDC reduces the difference to 6.0%. This is due to the improved magnet density for CDC compared to CCM.

The motors with all of the three types of magnets were tested using a computer controlled dynamometer. Figures 3 and 4 show the comparison of the motor performance for different magnets before thermal aging. From these figures, it is observed that to produce the same torque comparable current is drawn by the motor with anisotropic Neo and the motor with CDC isotropic bonded Neo. It is also observed that the motor with CCM isotropic bonded Neo draws more current compared to the motor with a magnet produced by CDC.

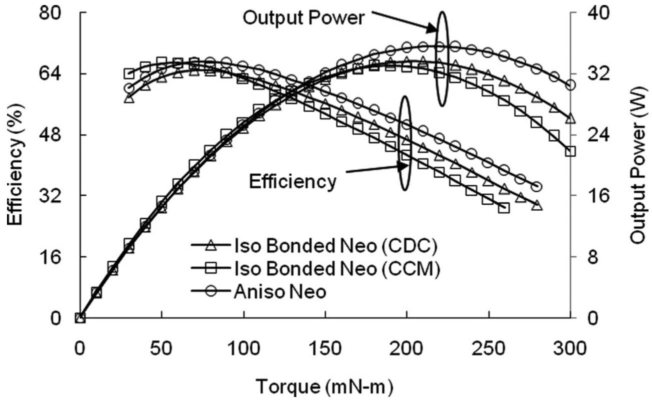

FIG. 6. Variation of efficiency and output power of seat motor after thermal aging.

To study the effect of thermal aging on various magnets and then on the motor performance, the test motors were kept (unoperational) in an oven at 120 °C for 24 hs and then again the k_b and motor performance was evaluated. The value of k_b for the motors with different magnets is given in Table III. Here it can be seen that the reduction in k_b is the highest at 2.65% for the anisotropic Neo magnet compared to 1.26% and 2.12% for isotropic bonded Neo magnets produced using CCM and CDC method, respectively. The motor performance after thermal aging is shown in Figs. 5 and 6, from which it can be observed that the difference in performance for anisotropic Neo and isotropic bonded Neo from CDC method is reduced and becomes almost the same. Hence isotropic bonded Neo magnets produced by CDC will be the ideal choice for applications where performance needs to be greater than that which is available with CCM Neo magnets. CDC isotropic magnets offer the performance of bonded anisotropic materials with better thermal stability and without difficulties associated with bonded anisotropic Neo.

IV. CONCLUSIONS

The net shaped and thin walled ring magnet produced using CDC technology has much higher density, 6.22 g/cm^3, compared to the isotropic bonded Neo magnets produced commercially by CCM, 5.88 g/cm^3, an increase of 5.8%. The airgap flux for the magnet produced by the proposed method is 6% more compared to the commercial isotropic bonded Neo magnet. After exposure to high temperature the difference in the motor performance for anisotropic Neo and isotropic bonded Neo using CDC is comparable due to the superior thermal aging stability of isotropic bonded Neo. Isotropic bonded Neo magnets produced by CDC will be the ideal choice for applications and where slightly higher magnetic property is needed compared to conventional bonded Neo.

[1] B. M. Ma, J. W. Herchenroeder, B. Smith, M. Suda, D. N. Brown, and Z. Chen, J. Magn. Magn. Mater. **239**, 418 (2002).

[2] J. Ormerod and S. Constantinides, J. Appl. Phys. **81**, 4816 (1997).

[3] D. Li, S. Gaiffi, D. Kirk, K. Young, J. Herchenroeder, and T. Berwald, J. Appl. Phys. **85**, 4871 (1999).

[4] D. F. Witherspoon, D. W. Massey, A. T. Mozhi, D. L. Kruczynski, and J. M. Ryan, U.S. patent 6767505 (27 July 2004).

[5] K. Nagarathnam, D. Trostle, and D. Massey, "Process Optimization and Properties of Select Non-Ferrous Materials Using High Pressure Combustion Driven Compaction," 2008 International Conference on Tungsten, Refractory & Hardmaterials VII Powder Metallurgy & Particulate Materials, Washington DC, June 8–12, pp. 3–92 to 3–106 (2008).

[6] K. Nagarathnam, D. Trostle, D. Kruczynski, and D. Massey, PM2 TEC 2004, Materials Behavior and Manufacturing Aspects of High Pressure Combustion Driven Compaction P/M Components, June 13–17, 2004, Chicago, IL, pp. 1–15, (2004).

[7] K. Nagarathnam and D. Massey, U.S. patent pending-application #61/396,231.

[8] S. Ando, Y. Mine, K. Takashima, S. Itoh, and H. Tonda, J. Mat. Proc. Tech. **85**, 142 (1999).

[9] S. Guruswamy, M. K. McCarter, J. E. Shield, and V. Panchanathan, J. Appl. Phys. **79**, 4851 (1996).