2. POWER ELECTRONICS

A. Low-Cost, High-Energy-Product Permanent Magnets

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Objective

- Develop a low-cost process to fabricate anisotropic NdFeB permanent magnets (PMs) with an increase of up to 25% in energy product (a measure of the torque that a motor can produce for a given magnet mass).

Approach

- Use high fields of superconducting solenoids to improve magnetic grain alignment while pressing compacts for sintering, thus producing higher-performance magnets.
- Develop a batch-mode press that enables alignment of the magnetic domains of NdFeB powders in the higher-strength magnetic fields created by a superconducting solenoid.
- Characterize, compare, and correlate engineering and microscopic magnetic properties of magnets processed under varying conditions, including some in current production.
- Use a reciprocating feed to automate the insertion of loose and compacted magnet powder into, and its removal from, the steady magnetic field of a superconducting solenoid.

Accomplishments

- Achieved energy products within 10% of the theoretical maximum by optimizing batch-mode alignment/pressing of cylindrical axial-die-pressed PMs in a 9-Tesla (T) superconducting solenoid. The magnetic properties are comparable to those of the more expensive magnets made by the transverse-die pressing technique.
- Achieved energy product improvements of 15% for thin near-final-shape magnets, production of which is the current cost-saving thrust in the PM industry. Additional PMs made with relatively small length-to-diameter ratios (L/D <0.5) support the previous findings.

- Completed preliminary conceptual design of a vacuum die-filling and powder-pressing system to alleviate cracking that was observed in fabricating compacts with low L/D ratios (<0.25). The vacuum system will also speed up the powder-filling and pressing process, necessary for industrial acceptance of this new technology.
- Carried out an electromagnetic modeling study of grain alignment in powder compacts. Analyses were carried out by assuming that all the magnetic particles are either initially oriented in the direction of the alignment field or initially randomly oriented. The results of both analyses show that the distortion of the alignment field (caused by the self-field of the compact) is inversely proportional to the magnitude of the alignment field. These results will help to provide scale-up design rules to industry.

Future Direction

- Complete the design and fabrication of the vacuum powder-filling and compact-pressing system and of the pressurized compact ejection system. Demonstrate that compacts can be made at rates acceptable to industry.
- Conduct an economic study comparing the estimated cost of PM manufacturing in continuous-mode operation using the superconducting magnet, with the cost of a conventional system currently used by industry.
- Continue to collaborate with Magnequench UG on PM fabrication and property measurements, with Oak Ridge National Laboratory (ORNL) on microstructure characterization of the finished PM samples, and with Ames Laboratory on processing the NdFeB powder for bonded PMs.

Introduction

The strength of sintered NdFeB magnets greatly depends on the method by which the compact is magnetically aligned and pressed. Large blocks can be made by cold-isostatic pressing that are within 5% of their theoretical maximum, but these must be sliced, diced, and ground to final shape, making the magnets very expensive. Magnets that are axial-die-pressed and sintered to near-final shape are the least expensive to make, but they have magnetic properties farthest from their theoretical maximums. The current industry goal is to fabricate higher-energy-product magnets by near-net-shape processing to avoid expensive machining operations. The major objectives of this project are to increase the energy product of the sintered PMs by 10 to 15% (to within ~10% of the theoretical maximum) and to develop low-cost methods of production for high-energy-product, near-final-shape PMs. The higher-performance magnets will replace ones made by traditional powder metallurgy processing and enable significant size and weight reductions in traction motors for hybrid vehicles.

Approach

Our approach is to align the NdFeB powder in a superconducting magnet, which can generate magnetic fields much higher than those generated by the electromagnets presently used in industry. Alignment of the powder in these higher magnetic fields improves the properties of the PMs. To develop a low-cost mass-production method for high-energy-product PMs, we plan to design, fabricate, and demonstrate the reciprocating axial-die-press system for automation.

Previously, a 9-T superconducting solenoid was procured and made operational. Production-grade magnet powder was obtained from Magnequench UG. The 3- to 5-micron single-crystal grains of powder were aligned and compacted at Argonne National Laboratory (ANL). Then the anisotropic compacts, with their grains mechanically locked in place, were returned to Magnequench UG for sintering, annealing, machining, and measuring of engineering magnetic properties. Finally, selected PMs were sent to ORNL for measurement of microscopic properties and texture (the alignment of the crystals' easy magnetic axes).

Previously, we had demonstrated that significant improvement of energy product (10–15%) can be achieved by using higher alignment fields (>2 T).[1] Industry considers an improvement in energy product of as little as 3–5% compared with current PMs to be significant. The progress achieved so far is based on a batch process at ANL. Major issues remaining for acceptance of the technology by industry are (1) to demonstrate that PMs can be made at a much faster rate than in the batch process

and (2) to demonstrate that near-final-shape PMs can be processed, resulting in greater cost reduction.

Results

In FY 2003, we continued the previous study with emphasis on a smaller L/D ratio (<0.25) where improvement in energy product is expected to be greater. The most effective use of the high alignment fields that can be provided by superconducting solenoids is in making near-final-shape magnets. Their finite and usually short length in the direction of magnetization makes alignment of the powder grains especially difficult. When subjected to a uniform alignment field, the powder in the die cavity develops a highly nonuniform self-field. Because grains align along the total field lines, unidirectional alignment can be achieved only by increasing the strength of the applied alignment field until the effects of the self-field become negligible. Because the self-field distortion becomes greater for shorter magnets, there will always exist short magnets that conventional 2-T electromagnets cannot adequately align.

A 1.125-in. die and punch system was used in the present study in order to achieve an L/D ratio smaller than 0.25. A large number of powdered compacts were processed under various conditions. However, all the samples were observed to have hairline cracks after ejection from the die and eventually broke into pieces. Figure 1 shows one of the cracked samples.

Figure 1. Photograph of a cracked compact after ejection from the die.

A number of factors could have caused the powered compacts to crack (some were suggested by our industrial partner, Magnequench UG). They include

- Maximum compact pressure and duration
- Rate of pressure loading and unloading (trapped air)
- Powder fill density
- Lubricant (type and amount)
- Magnetic field for alignment
- Die/punch geometry (e.g., clearance, punch diameter, taper angle of die)
- Oxygen content
- Powder homogeneity and filling procedure
- Compact ejection pressure

We have investigated all these factors and have concluded that the most likely causes for compact cracking are either air trapped during powder compaction and/or radial stress during compact ejection from the die. The production-grade magnet powder, received from Magnequench UG, is porous and contained a lot of air. If sufficient time and clearance are not provided during powder compaction, air will be trapped in the compact. The trapped air can subsequently cause the compact to crack when the pressure is released. This is a well-known problem for this type of process. The other likely cause for compact cracking is the radial stress during compact ejection from the die. Figure 2 shows the stresses on the compact during pressing and during compact ejection for the current system. During compact ejection, the axial stress is released while the radial stress is still very large; this could cause the compact to crack.

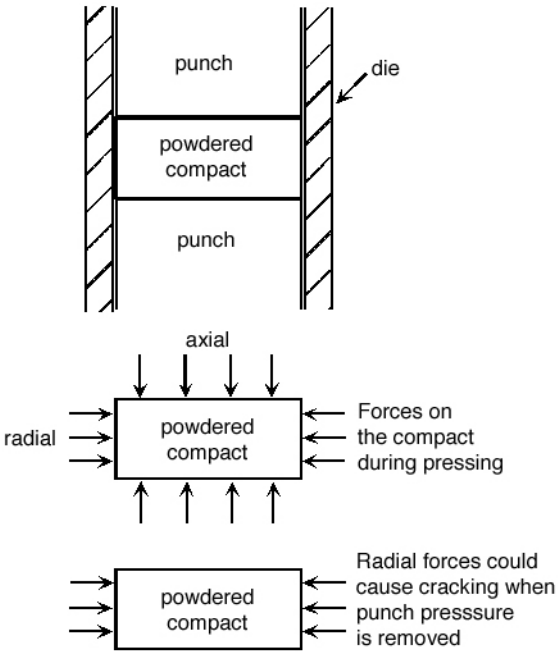

Figure 2. Schematic diagram showing probable cause of cracking during compact ejection from the die.

The industrial practice is to eject the compact under axial pressure. In order to eject the compact under pressure, the current set-up must be upgraded.

To address the issues of trapped air and compact ejection under pressure, we came up with an innovative method of filling the die and pressing the compact under vacuum. Using the vacuum system will reduce the trapped air in the powder significantly, which (1) may alleviate the cracking problem, (2) will increase the powder-pressing speed, and (3) will speed up the powder-filling process. The last two improvements are also a necessary step toward demonstration of a process that can manufacture PMs at a much faster rate than the batch mode. By using the vacuum-compatible die, we also came up with a preliminary conceptual design for a system that can eject the compact under pressure, which may alleviate the cracking problem described previously.

To understand the effect of the self-field of the magnet powder on the distortion of the alignment field, we carried out an electromagnetic study of grain alignment in powder compacts using the computer code Opera developed by Vector Fields, Inc. Previously, we conducted the analysis by assuming that all the magnetic particles are initially oriented in the direction of the alignment field. The results provided a lower bound on the distortion of the field lines. In the present analysis, we assume more realistically that the magnetic particles are initially randomly oriented. Figures 3 and 4 show the calculated field lines of one-quarter of a PM for alignment fields of 1 and 8 T, respectively. These calculations were carried out using the same powder density (3.5 g/m^3) and the same L/D ratio (0.643). The field lines will all be parallel to the z-axis if there is no distortion. It is clear that distortion of the alignment field is substantial when the alignment field is 1 T (Figure 3). The distortion decreases with increasing alignment field. At an alignment field of 8 T, the distortion becomes very small (Figure 4).

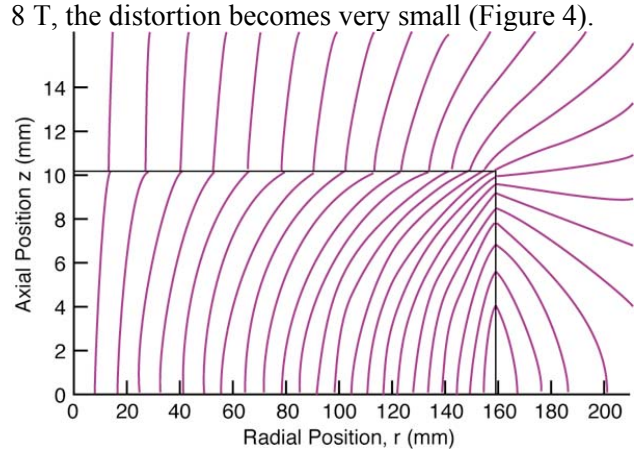

Figure 3. Field lines (one-quarter) for compact partially pressed to mechanical lockup. Alignment field H =1 T. Parameters: ρ_l = 3.5 g/m^3, L/D = 0.643, B_0 = 0.65 T.

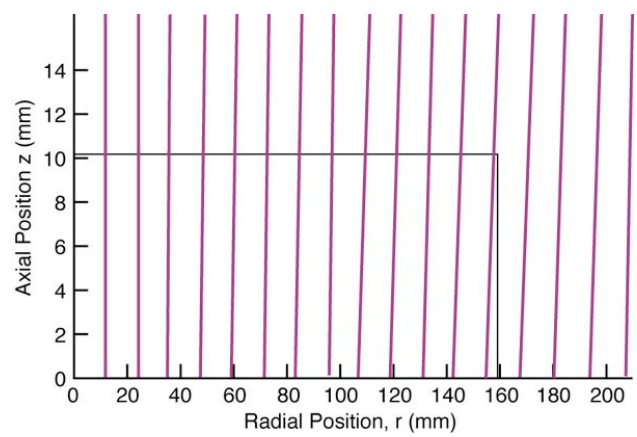

Figure 4. Field lines (one-quarter) for compact partially pressed to mechanical lockup. Alignment field H = 8 T. Parameters: ρ_l = 3.5 g/m^3, L/D = 0.643, B_0 = 0.65 T.

Figure 5 shows the comparison of the field line distortion between the previous analysis (assuming

magnetic particles are initially oriented in the direction of the alignment field) and the current analysis (assuming magnetic particles are initially randomly oriented). B_r and B_z are defined as the radial and the axial components of the magnetic flux density B, respectively. The vertical axis represents the volume average of the ratio B_r/B_z, which is a good measure of the overall distortion of the field lines. As expected, Figure 5 shows that the distortion of the field lines is greater if the magnetic particles are initially randomly oriented,

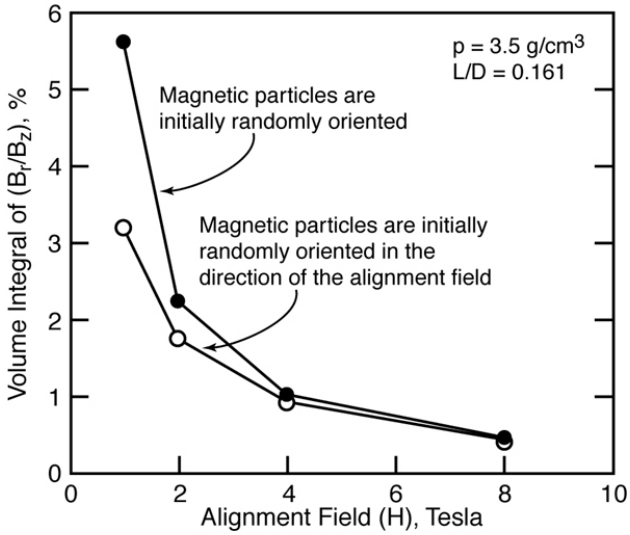

Figure 5. Comparison of field line distortion between previous and present analyses.

compared with the case where the magnetic particles are initially oriented in the direction of the alignment field. Both analyses show that the distortion of the field lines decreases with increasing alignment field.

Conclusions

Previously, we demonstrated that significant improvement of energy product (10–15%) can be achieved by using higher alignment fields (>2 T). Industry considers an improvement of 3–5% in the energy product of current PMs to be significant. Major issues remaining for acceptance of the technology by industry are (1) to demonstrate that PMs can be made at a much faster rate than in the batch process, and (2) to demonstrate that near-final-shape PMs can be processed, resulting in greater cost reduction. In FY 2003, we continued to fabricate powdered compacts with an even smaller L/D ratio (<0.25) by using a larger (1.125–in.) die and punch set. However, all the samples were observed to have cracks after ejection from the die. With the help of industrial partner Magnequench UG, we identified two factors that probably caused the compacts to fail: trapped air in the powdered compact during pressing and the radial stress during ejection of the compact from the die.

To alleviate the trapped air problem, we decided to use a vacuum-compatible die. We have completed a preliminary conceptual design of a vacuum die/punch set. The system also allows the present system to be modified so that the compact can be ejected under pressure, which also may alleviate the cracking problem. We have completed a preliminary conceptual design for upgrading the existing system for just this purpose.

To help us understand and quantify the distortion of alignment field due to the self-field of the magnet powder, we continued the electromagnetic study of grain alignment in powder compacts using the computer code Opera. Previously, we assumed that all the magnetic particles are initially oriented in the direction of the alignment field. In the present analysis, we assume more realistically that the magnetic particles are initially randomly oriented. As expected, the results show that the distortion of the field lines is greater if the magnetic particles are initially randomly oriented. Both analyses show that the distortion of the alignment field lines decreases with increasing alignment field.

In FY 2004, we plan to complete the design, fabricate the vacuum die/punch set, and demonstrate that PMs can be manufactured at a much faster rate than with the batch process. We will also perform an economic study comparing the estimated cost of the present superconducting system with that of the conventional system used by industry. Our long-term and final goal is to demonstrate the feasibility of competitive factory operation by designing, fabricating, and operating a reciprocating press in continuous-mode operation.

References

1. *2002 Annual Progress Report, Automotive Propulsion Materials*, U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of FreedomCar and Vehicle Technologies, Washington, D.C.

FY 2003 Publications/Presentations

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T. M. Mulcahy, J. R. Hull, E. Rozendaal, J. H. Wise, and L. R. Turner, "Improving Sintered NdFeB Permanent Magnets by Powder Compaction in a 9-T Superconducting Solenoid," *J. App. Phys*. **93(**10), pt. 3, 8680–82 (2003).

Y. S. Cha and J. R. Hull, "Low-cost High-energy-product Permanent Magnets," presented at the Capacitor and Magnetic Materials, Power Electronics/Electric Machinery Program Review, U.S. Council on Automotive Research, Southfield, Michigan, May 13, 2003 (to be included in the proceedings).