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# NdFeB MAGNETS ALIGNED IN A 9-T SUPERCONDUCTING SOLENOID

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Commercial-grade magnet powder (Magnequench UG) was uniaxial die-pressed into cylindrical compacts, while being aligned in the 1-T to 8-T DC field of a superconducting solenoid at Argonne National Laboratory. Then, the compacts were added to normal Magnequench UG production batches for sintering and annealing. The variations in magnet properties for different strengths of alignment fields are reported for 15.88-mm (5/8-in.) diameter compacts made with length-to-diameter (L/D) ratios in the range 0.25 and 1. The best magnets were produced when the powder-filled die was inserted into the active field of the solenoid and then pressed. Improvements in the residual flux density of 8% and in the energy product of 16% were achieved by increasing the alignment field beyond the typical 2-T capabilities of electromagnets. The most improvement was achieved for the compacts with the smallest L/D ratio. The ability to make very strong magnets with small L/D, where self-demagnetization effects during alignment are greatest, would benefit most the production of near-final-shape magnets. Compaction of the magnet powder using a horizontal die and a continuously active superconducting solenoid was not a problem. Although the press was operated in the batch mode for this proof-of-concept study, its design is intended to enable automated production.

## 1 Introduction

### 1.1 Overview

The cost, weight, and volume of existing electric traction motors are too high to meet established performance targets for hybrid vehicles. One of the most promising means to reduce weight and volume in a traction motor is by increasing the energy product of the sintered permanent magnets (PMs). Higher energy magnets will reduce not only the weight of the PMs, but also, by a similar fraction, the weight in the balance of a motor producing the same torque.

In this investigation, a 9-T high-field superconducting solenoid (SCM) is used to align the powder and improve the energy product of axial die-pressed magnets by up to 16%. Weight reductions to 16%, and associated lower costs, are anticipated. Other methods may produce higher performance magnets, but axial die-pressing was selected for investigation because of its potential to produce lower cost magnets in near final shape.

A reciprocating press is envisioned to achieve production rates typical in industry today. In operation, powder would be loaded in one die that is moved momentarily outside of the superconducting solenoid, while the powder would be pressed in another die that is moved momentarily into the solenoid. This study has demonstrated the feasibility of moving a powder-filled die into the bore of an operating superconducting solenoid for pressing.

### 1.2 Superconducting Solenoid for Axial Die-Press Alignment

Pulsed electromagnets have nearly achieved the theoretical limits for anisotropic NdFeB grain alignment during transverse die pressing, isostatic pressing, and rubber-isostatic pressing (RIP) of the magnet powder into compacts [1-4]. For these methods of pressing, typically, large magnet blocks are produced, and the final magnets are cut, machined, and ground from the block. A goal

of this investigation is to improve the grain alignment, and therefore the energy product, of axial die-pressed magnets, especially near-final-shape magnets with small L/D ratios. Clearly, the cost of fabrication is reduced if near-final-shape magnets can be produced that eliminate cutting and machining. To achieve this goal, a high-field superconducting solenoid was chosen for two reasons. First, its higher fields can overcome larger friction between the grains, and thus rotate more grains into alignment. Second, its higher applied fields were deemed necessary to produce a uniform alignment field by overwhelming the self-demagnetization field created by finite-length powder fills. Preliminary electromagnetic code calculations showed significant distortions in the resultant field for applied alignment fields well above the 2 T that is typical of electromagnets used by industry.

## **2 Test Facility**

A 9-T superconducting solenoid was chosen to incorporate into a test facility for pressing at Argonne National Laboratory (ANL). The purpose of the facility is to demonstrate that the magnetic properties of axial die-pressed PMs can be significantly improved by compacting them in the higher alignment fields available with an SCM. Higher fields are expected to increase the grain alignment of the compacts and, thus, the magnetic properties of the PMs. However, grain alignment was not measured directly. Improvements are assessed by comparing the residual magnetic flux densities and energy products of PMs that are compacted in alignment fields which vary from 1 to 8 T. For this proof-of-concept study, the facility is manually operated; however, operations critical for automation also are proven.

### *2.1 Reciprocating Press Concept*

To achieve automated operation, the design concept chosen was to reciprocate the press into and out of the active SCM. A similar concept has been used with superconducting solenoids in the clay separation industry [5]. An unorthodox press-in-tube device for axial die-pressing in a batch (manual) mode was designed and built by Ability Engineering Technology, Inc. See Figs. 1 and 2. This device met the magnetic and geometric constraints created by the SCM.

For this proof of concept operation, a simple die and punch set made of nonmagnetic materials is filled with powder in a nitrogen atmosphere glovebox and then loaded into the nonmagnetic press tube. Next the cantilevered press tube is inserted horizontally into the warm bore tube on an aluminum carrier manually advanced along an aluminum track. The press tube is precisely centered in the bore. Compaction is achieved by pressing the punches between the base plug at the end of the press tube and the hydraulic cylinder mounted on the opposite end. Finally, the press tube is extracted from the bore tube and the die containing the compact is removed from the press tube and transferred to a glovebox, where a hand press is used to eject the compact.

In a commercial operation, the superconducting solenoid would be integrated into a standard press design, which includes continuous and individual position controls for the die and each punch. These controls would enable automated powder filling at the press, through a closed system of filling bins, tubing and shoes. Also, compact extraction would occur at the press.

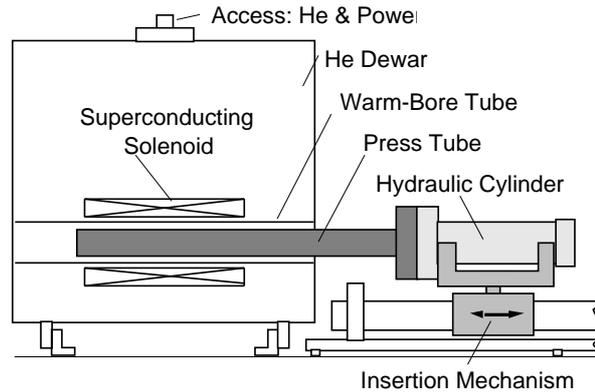


Figure 1(a). Press tube inserted into superconducting solenoid located in helium dewar.

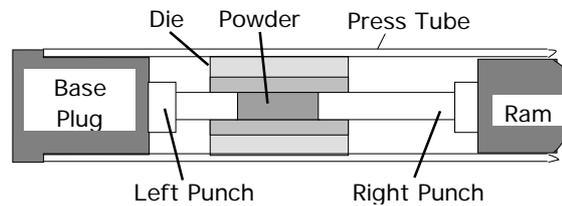


Figure 1(b). Press tube interior. Shows powder in floating die being pressed between hydraulic ram and base plug.

The press tube and ram are made from very low magnetic permeability materials ( $\mu_r < 1.002$ ). The hydraulic cylinder was custom made, by Atlas Cylinders, Inc., from stainless steel with a low permeability ( $\mu_r < 1.01$ ). Electromagnetic code calculations determined the magnetic field of the SCM and the forces on the powder and compacts [6]. The length of the press tube was chosen to enable access to the SCM centered 38 cm within its helium dewar, and to locate the more magnetic hydraulic cylinder in the far field of the SCM, where the field gradient is weak. Also, the press tube could be rotated, which allowed die/punch set insertion in an even weaker field. See Fig. 2. The insertion mechanism and press tube were sized to withstand the magnetic forces and behave essentially as rigid bodies.

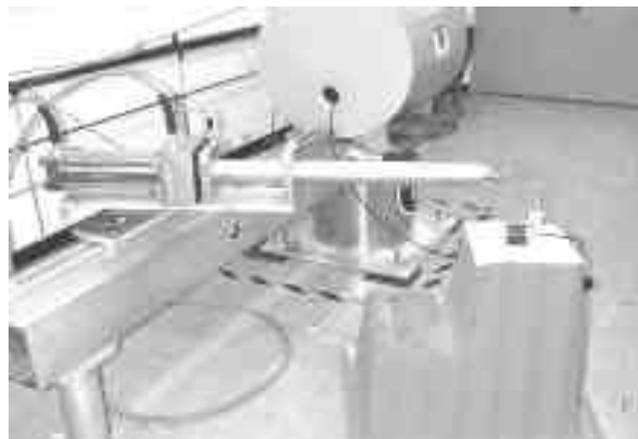


Figure 2. Die insertion into press tube, rotated into loading position. Hydraulic cylinder on back (left) end of press tube.

For an automated factory, press operations are envisioned to occur from both ends of the SCM bore, where the extraction of one press tube is synchronized with the insertion of the other. Powder filling of one die would occur while another compact is being pressed. The design of both presses and the transport mechanism would minimize magnetic forces during extraction and insertion, by selective location of the powder, compacts and magnetic shimming at opposite ends of the SCM. Magnetic shielding of the SCM would allow powder filling of the die and compact ejection, when that press is in the extracted position.

## *2.2 Superconducting Solenoid (SCM)*

A SCM was purchased from Cryomagetics, Inc. This device has a horizontal, 7.6-cm-diameter warm bore and is similar to other Cryomagetics designs. The length of the bore tube is 76.2 cm. The magnitude of the steady field in the bore of the SCM can be continuously varied up to 9 T. The powder can be aligned in a field that is uniform within 5%, over a volume that is large enough to press 2.54-cm-diameter cylindrical PMs that are over 10-cm long. SCM cooling was achieved with only liquid helium and superinsulation. A cryo-cooler and magnetic shielding for the SCM were not included, because these additions would have more than doubled the initial cost. Both additions will be needed for acceptance into factory operations. In retrospect, the SCM should have been shielded for laboratory use. The laboratory was large enough to isolate the far field and satisfy all environmental, health, and safety issues, but the cost of shielding nearby computer monitors, which are sensitive to the millitesla level, nearly equaled the cost of initially shielding the SCM.

The robustness of the mechanical components holding the SCM, in its liquid helium dewar, were specifically designed to allow for insertion and extraction of the magnetic powder and compacts, while operating at 9 T. Calculations showed that forces along the magnet axis could be as large as 3402 N (750 lb). Prior to acceptance of the SCM, the magnetic field in the bore was verified at the manufacturer, as was the SCM support structure. A piece of steel was inserted into and extracted from the SCM operating at 9 T, which created the maximum magnetic forces expected.

The 42,000-turn SCM was 40-cm long and had inner and outer diameters of 12.75 cm and 20.1 cm, respectively. Each end had an additional 2800-turn, 7.9-cm long shim coil. The diameter of the Nb-Ti/Cu wire in the main coil and the shim coils was varied to achieve the magnetic field uniformity desired. A 75-A powder supply was more than adequate to operate the SCM at 9 T. For reasons of laboratory safety only, the SCM was operated in the power mode, rather than the persistent mode. Between uses, the SCM was de-energized. Ramp times were about 0.2-T/minute. Superconducting solenoids with much higher rates are available at additional cost. In commercial operation with a reciprocating die, the field should remain constant, and no ramping should be required. In retrospect, heating coils should have been included to intentionally quench the solenoid. After several cycles, remnant fields of 5 to 10 mT, with sharp axial gradients, were present at each end of the SCM. The supercurrents circulating around the diameters of the wires that were responsible for remnant fields can only be removed by quenching. When operating at high fields, the remnant fields were not a concern. But part of the proof of concept testing included the removal of loose magnet powder from the de-energized SCM bore. Custom means of shielding these specimens had to be designed and used.

### 2.3 Die and Punch Set

A 5/8-in. axial-die and punch set was designed in consultation with Magnequench UG, Inc., the permanent-magnet manufacturer, and Bronson and Bratton, Inc., the tooling fabricator. The set was made using very low magnetic-permeability material ( $\mu_r < 1.002$ ), which will not affect significantly the uniformity of the SCMs magnetic field or the alignment of the magnet powder. Still, when operating at 8 T, a force of 136 N was required to extract the empty die/punch set from the SCM. The die insert and the punches were made of nickel carbide, while the die case was made of Inconel 718. Tight diametrical clearances ( $< 0.025$  mm) were required to maintain alignment of this simple die and punch set. The tooling was polished to mirror finishes, and very-light coatings of stearic acid lubricants were used to ensure "floating die" operation. Clearly, tool steel with carbide tips would be difficult to use in an SCM's reciprocating press.

### 3 Permanent Magnet Results

More than 250 NdFeB cylindrical compacts have been pressed in the ANL test facility, using production-grade magnet powder obtained from Magnequench UG. Subsequently, many batches of the anisotropic compacts, with their grain orientation mechanically locked in place, were returned to Magnequench UG. As part of normal production runs, the compacts were sintered and annealed, and the PM faces were ground flat and parallel, before their demagnetization curves and/or residual flux densities were measured using hysteresisgraphs and Helmholtz coils. The first PMs had properties that were far from optimal. Thus, in cooperation with Magnequench, a significant effort was made to optimize pressing at ANL.

Different press loads, press rates, lubricants, and powder fill techniques were studied and changed. Prior to optimization, the dies were gravity filled in a glovebox, and the punches were fully inserted to the fill level. The magnetic properties were most significantly improved by filling the die to powder densities less than can be achieved by gravity. However, leaving headroom in powder-filled die cavities was not a feature originally included in the design of the Argonne axial-die press facility. To maintain headroom, split-ring plastic constraints were attached to each punch, as shown in Fig. 3, where the upper right punch is positioned in the die, and the lower left punch is inserted after the powder fill. The friction on each ring was calibrated to hold during insertion into an active superconducting solenoid, but slipped when compaction loads were applied.

The results of the fill-density optimization study for cylindrical compacts with an L/D ratio  $\sim 1$  are shown in Fig. 4, where the maximum energy product, BH<sub>max</sub>, is given for various densities. The alignment fields were applied just before and during the pressing of these compacts. By decreasing the fill density by  $\sim 20\%$  below the gravity-fill density levels, the energy product was improved by  $\sim 20\%$  for a 4-T alignment field. The same optimal fill density was found for compacts aligned at 8 T. Subsequent pressing used the same fill density.

The compacts aligned at 8 T (see Fig. 4) were made as part of a study to correlate energy-product improvements with increases in the alignment field, again for compacts with L/D  $\sim 1$ . The results are summarized in Fig. 5. The maximum energy product, BH<sub>max</sub>, was increased  $\sim 12\%$  by tripling the maximum 2-T alignment field available with electromagnets. The increase was the same for the first magnets made and for magnets made after the processing was optimized, but the optimized magnets had 30% higher energy products. Unexpectedly, the best magnets (solid symbols) were made when the alignment field was always on. This condition simulates the severe

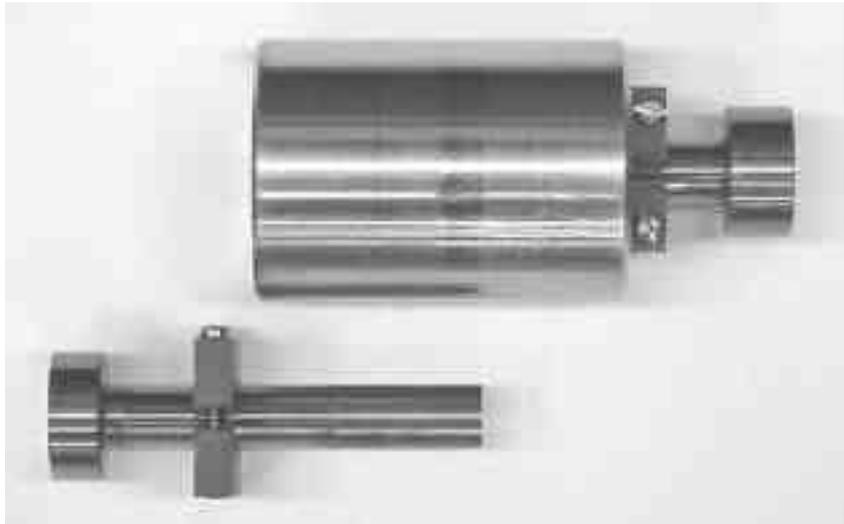


Figure 3. Split rings on punches that maintain die-cavity headroom.

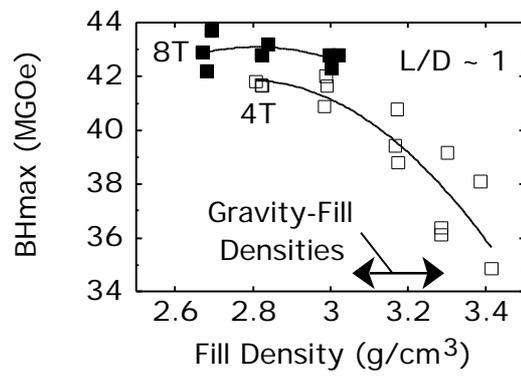


Figure 4. Maximum energy product as function of fill density.

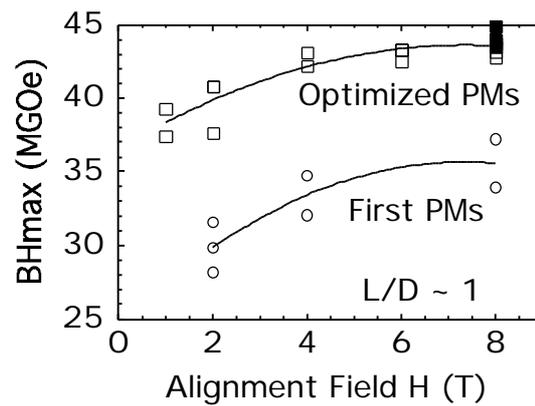


Figure 5. Maximum energy product as function of alignment field for L/D ratio ~ 1.

field gradients that loose powder in the die would experience during insertion into an operating superconducting solenoid by a reciprocating press. Of most importance, these maximum energy products are comparable to those of more expensive magnets made by the transverse-die-pressing technique. About 92% of the theoretical maximum was achieved. Thus, what was initially considered a potential serious impediment to using superconducting solenoids should not be a problem, and could actually result in a cost savings.

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 only be achieved by increasing the strength of the applied alignment field until the effects of the self-field become negligible. Since the self-field distortion becomes greater for shorter magnets, there will always be short magnets that the 2-T electromagnets of industry cannot adequately align. Clearly, the higher fields produced by a superconducting solenoid can provide the necessary alignment.

A study of near-final-shape cylindrical magnets was performed for compacts with  $L/D = 0.25$ ,  $0.50$ , and  $0.73$ . The results are given in Fig. 6. The remnant magnetization,  $B_r$ , of the shortest magnets, with a compact  $L/D = 0.25$ , improved the most. Quadrupling the alignment field from 2 T increased  $B_r$  by 8%. This is equivalent to a 16% increase in the maximum energy product, since  $BH_{max}$  is proportional to  $B_r^2$ . The magnets made from compacts thicker than  $L/D > 0.5$  did not appear to suffer self-field effects. Length-to-diameter ratios smaller than tested are common for near-final-shape magnets, but such magnets could not be accurately made and measured with the small diameter die (5/8-in.) available. Even larger improvements in energy product are expected for  $L/D < 0.25$ .

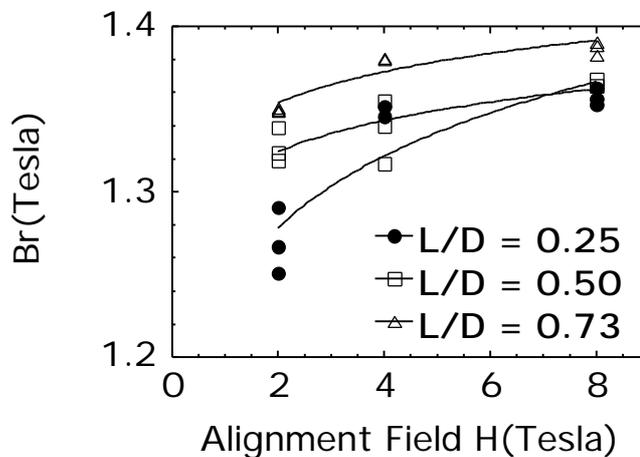


Figure 6. Remnant magnetization as function of alignment field for  $L/D = 0.25$ ,  $0.50$ , and  $0.73$ .

#### 4 Conclusions

Magnets were routinely made with an axial-die press. The maximum energy product of such magnets was improved to the same quality as the more expensive magnets obtained by transverse die-pressing. This, alone, represents an opportunity for significant cost savings. For relatively long magnets, the maximum energy products improved by about 12%. For near-final-shape magnets, the improvements were greater, at least 16%.

Use of a reciprocating feed to automate the alignment and pressing of magnet powder in a superconducting solenoid was shown not to be an issue. The best magnets were made when batch processing simulated the conditions of the reciprocating feed. In particular, the magnetic field was on when the loose magnet powder in the die cavity was inserted into the bore of the solenoid. Most important, these conditions produced the best magnets. The energy product was within 92% of its theoretical maximum. Apparently, insertion of loose powder into the field gradient of the superconducting solenoid provides a form of magnetic die filling that improves grain alignment.

#### Acknowledgments

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