3-D Particulate Modeling for Simulation of Compaction in Magnetic Field

Harunori Kitahara, Hidetoshi Kotera, and Susumu Shima

***Abstract*—The purpose of this study is to investigate the behavior of magnetic powders during compaction in an applied magnetic field, which is a common manufacturing process for producing permanent magnets. We employ a nonspherical axi-symmetric particle model and carry out simulation of compaction in a magnetic field to study the alignment of the easy axes. Compacting and lateral pressures appear to change by the application of magnetic field. The results of compacting pressures show qualitative agreement with experimental ones, and the alignment of the easy axes is significantly influenced by the application of magnetic field. It is shown that alignment of the easy axes obtained by the simulation is supported by experimental observations.**

***Index Terms*—Neodymium alloys, permanent magnets, powder magnetic materials, simulation.**

I. INTRODUCTION

PERMANENT magnets are usually made by compacting anisotropic magnetic powders in an applied magnetic field. Each particle has its easy direction of magnetization, and its alignment gives a great effect on the magnetic performance of the obtained permanent magnet. Depending on the shape of the magnet and on the direction of the easy axis, either of the two types of compaction are chosen in common (see Fig. 1); they are parallel compaction a), where the compacting direction is parallel to the direction of the applied magnetic field, and cross or transverse compaction b), where they are perpendicular to each other.

There have been many studies of properties of magnetic powder materials, but very few of the relationship between the magnetic performance of the final compact and compaction process. While experimental results on Nd–Fe–B powders suggest that the magnetic property of the permanent magnet made by transverse compaction is superior to that by parallel compaction, the reverse is true for the case of Sr–Ferrite powder [1], [2]. The reason has not been put forward so far. To investigate the effect of application of a magnetic field, we employed the PDM (Particle Dynamics Method) to simulate the motion of magnetic particles and obtained results that agreed qualitatively well with experimental ones [3], [4].

In this study, we simulated compaction of magnetic powder in a magnetic field and examined the relationship between density ratio and pressures in three perpendicular directions. We also performed experiments of compaction of Nd–Fe–B powder in a magnetic field. By comparing the two results, we discuss the micro-mechanical behavior of magnetic particles. We compared particles alignment obtained by the simulation and experimentally derived residual magnetic flux of the compact.

Manuscript received October 25, 1999. This work was supported in part by the Japan Atomic Energy Research Institute.

The authors are with the Department of Mechanical Engineering, Kyoto University, Japan (e-mail:{harry; kotera; shima}@mech.kyoto-u.ac.jp).

Publisher Item Identifier S 0018-9464(00)06609-7.

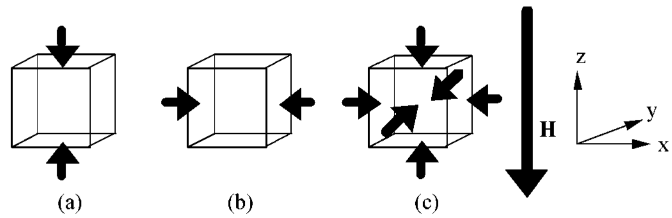

Fig. 1. Types of compaction in magnetic field: (a) Parallel compaction (b) Cross compaction (c) Isostatic compaction.

II. EXPERIMENT

In experiment, we used a Nd–Fe–B magnetic powder. We mainly performed cross compaction and additionally parallel compaction. The die is made of a nonmagnetic cemented carbide as in the real production of Nd–Fe–B magnet. For pressure measurement, we used anti-magnetism strain gauges affixed on the pressure measuring pins also made of nonmagnetic material. We confirmed that there was no effect of the applied magnetic field on the measured pressures. We sprayed mechanical oil on the die walls to minimize the friction between the die surface and the powder. After compaction, we sintered the compacts and measured the residual magnetic flux.

III. PARTICLE DYNAMICS SIMULATION

Principle of the PDM is similar to the ordinary Distinct Element Method. In PDM, we derive all the forces for each particle's and solve equations of motion in a step-wise manner. We, thus, calculate acceleration, velocity and therefore displacement for each particle. In the present simulation, it incorporates the Maxwell stress and the inter-particle force due to the applied magnetic field in addiction to the forces at contact that have been taken into account in the previous simulation of compaction process [5].

To express various particle shapes, we adopt a nonspherical particle model composed of parts of spheres as shown in Fig. 2(a), where d_p is the diameter and b is the height of the particle [3]. We define aspect ratio of the particle model as $\beta = b/d_p$. This model is capable of expressing various kinds of particle shape only by varying β. In this study, we used a mono-sized particle model of an aspect ratio of $\beta = 0.8$.

Anisotropic magnetic particles have their easy directions for magnetization. In an applied magnetic field, they are magnetized more strongly in these directions. We hereby assume that

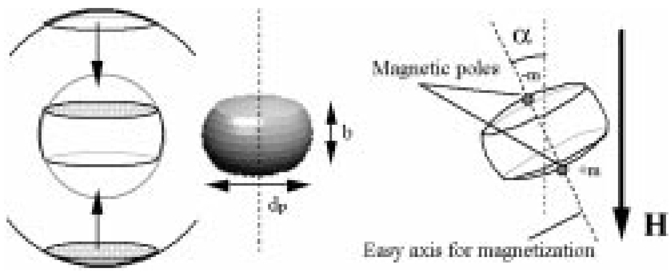

Fig. 2. Non-spherical particle model with parts of spheres: (a) Shape of particle (b) Model of magnetic pole.

TABLE I
MATERIAL PROPERTIES FOR CALCULATION

Density	7.50×10^3 [kg/m³]
Young's Modulus E	1.50×10^2 [GPa]
Particle mean diameter	1.00×10^{-3} [m]
Permeability μ	1.25×10^{-6} [Wb/(A m)]
Strength of magnetic field H	8.00×10^5 [A/m]
Strength of magnetization m_a	5.00×10^{-7} [Wb]
Number of particles	1000 [m/s²]
Acceleration of Gravity	9.8
Time step	0.5×10^{-6} [s]

hypothetical magnetic poles are induced at both sides of the particle as shown in Fig. 2(b). We assumed that the easy axis for magnetization of each particle coincides with the particle's axis. α is the angle measured from particle's easy direction for magnetization to the direction of the applied magnetic field. Thus an assembly of particles that gives a smaller α reveals a better magnetic performance.

For the PDM calculation, we consider three forces between particles: Hertzian repulsive force at contact, the Coulomb force between particles' magnetic poles, and force from the applied magnetic field. In the simulation, we ignore the inter-particle friction and friction between the particles and die walls. The material concerned is Nd–Fe–B magnetic powder, and we assumed that the strength of the applied magnetic field to be the one in the real manufacturing process. The material properties for calculation are listed in Table I.

In PDM simulation, the calculated pressures do not agree with experimentally derived ones, if we use Young's modulus of the fully dense material. One of the reasons is that the particles in the simulation are assumed to be composed of ideally smooth surfaces, which is not true for real powders. Therefore, we decreased Young's modulus of the particles so that the calculated pressure-density ratio curve approached the experimentally derived curve of the Nd–Fe–B powder.

We calculate the behavior of ferromagnetic particles in three types of compaction (see Fig. 1): (a) parallel compaction, (b) cross compaction and (c) isostatic compaction. We started compaction from a density ratio of 0.25 after filling in a parallelepiped cell or die cavity.

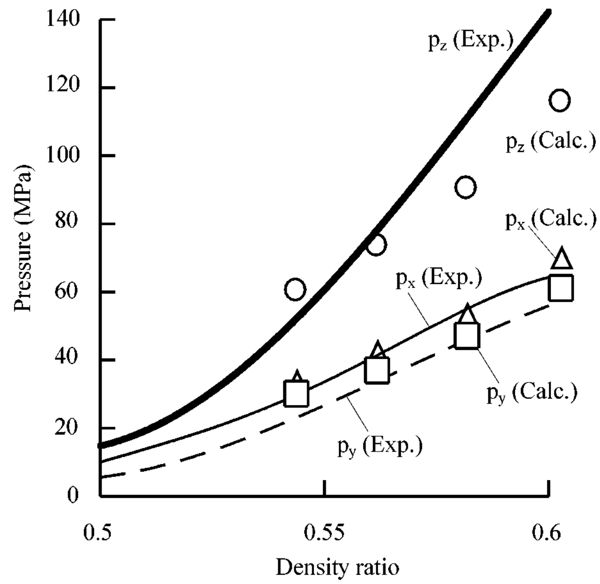

Fig. 3. Relationship between pressure and density ratio in cross compaction.

IV. RESULTS AND DISCUSSION

A. Effect of Applied Magnetic Field on Compaction Pressures

We simulated transverse compaction with application of a magnetic field from the initial stage to the final in a compaction process. Pressures calculated are shown by the symbols in Fig. 3. For the case where the magnetic field is applied, pressure p_x is higher than p_y throughout a compaction, while they were obviously the same without it. Although there is a difference in magnitude, the experimental results (shown by the lines in Fig. 3) support the simulated ones. The pressure difference would be attributed to the Maxwell stress and structural anisotropy induced by the magnetic field. We discuss it in the following.

In magnetic field, the Maxwell stress shown below affects the behavior of magnetic materials,

$$T_{ij} = H_i B_j - \delta_{ij} U^m \tag{1}$$

where $B_i = \mu H_i + M_j$ is the magnetization with μH_i being the magnet flux inside the material, M_j, the magnetic polarization, and magnetic energy U^m is expressed by

$$U^m = (H_i B_i)/2 \tag{2}$$

In cross compaction, the Maxwell stress reduces the pressure along the direction of magnetic field (p_z), and increases the pressures perpendicular to it (p_x and p_y). The magnitude of the pressure change is equal in all the directions. At a strength of magnetic field of 8.00×10^5 [A/m], for example, the calculated Maxwell stress is about 1[MPa] or so for the powder concerned at a density ratio of $\rho = 0.5$ or 0.6.

On the other hand, when the magnetic field is applied to the powder, the particles tend to behave in such a way that the assembly reveals a structural anisotropy; the particles change their directions to the applied magnetic field, and connect each other to construct chains in this direction. As shown later by the snapshots (see Figs. 6 and 7), they seem to behave like weak columns, and thereby they may affect the pressures.

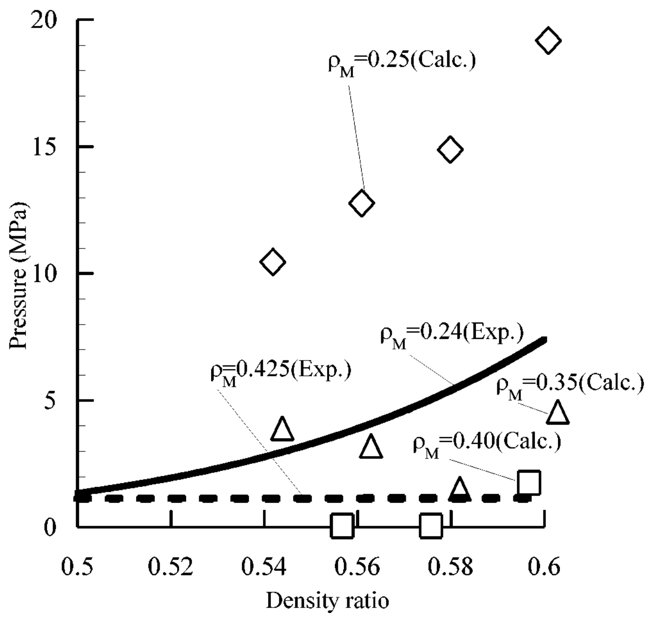

Fig. 4. Relationship between pressure difference p_{diff} and density ratio at various values of ρ_M.

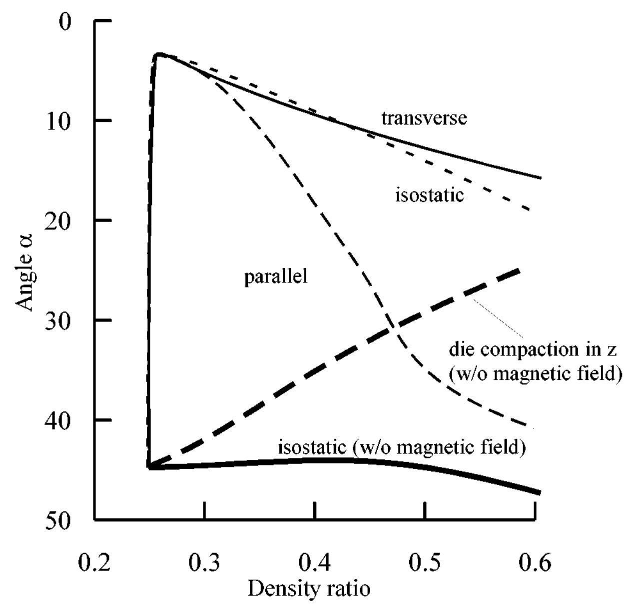

Fig. 5. Relationship between average angle α and density ratio in compaction of mono-sized particles.

Comparing with the estimated Maxwell stress, we see that the pressure difference due to the applied magnetic field obtained by both simulation and experiment is much larger. Although we are not aware of the magnitude of the pressure difference induced by the structural anisotropy, we may consider that this plays a major role.

To examine this more in details, we simulated the compaction with changing the density ratio at which the magnetic field (ρ_M) was started to apply. Fig. 4 shows the variation of pressure difference $p_{diff}(= p_x - p_y)$ with density ratio for three cases, i.e. $\rho_M = 0.25$, 0.35 and 0.40. Fig. 4 obviously shows that the lower the value of ρ_M, the larger is the pressure difference p_{diff}. For the case of $\rho_M = 0.4$, the magnitude is roughly in the order of the Maxwell stress. The experimental results shown by the lines in Fig. 4 also show the same tendency.

These results show that the main reason for the pressure difference due to the application of the magnetic field may be attributed to the structural anisotropy, and that the anisotropy may have been induced more easily when the magnetic field was applied at a lower density. In the case of transverse compaction with a lower ρ_M, the columns are compressed in the lateral direction as shown later, thus the total anisotropy would not change by subsequent compaction. Therefore, its effect on pressures increase as density ratio increases (see Figs. 3 and 4). For a higher ρ_M, on the contrary, there is not enough room for particles to rotate or rearrange. Accordingly, the structural anisotropy was not induced so much.

B. Effect of Compaction Mode on Alignment

Fig. 5 shows changes in the average angle α of particles' axes measured from z-axis with density ratio. α is almost zero just after the application of the magnetic field for any compaction type. As compaction proceeds, however, the angle increases, in particular, in the case of parallel compaction. This is due to that the columns of magnetic particles are inclined or collapsed during compaction as shown in Fig. 6. In the case of cross compaction, on the other hand, the columns built up in the z direction are compressed only in the lateral direction, thus the alignment is not worsened very much (see Fig. 7). In the case of isostatic compaction, the situation is similar, because all the particles are displaced toward the center of the cell and that the structure built up in the early stage of compaction may be kept without being destroyed significantly.

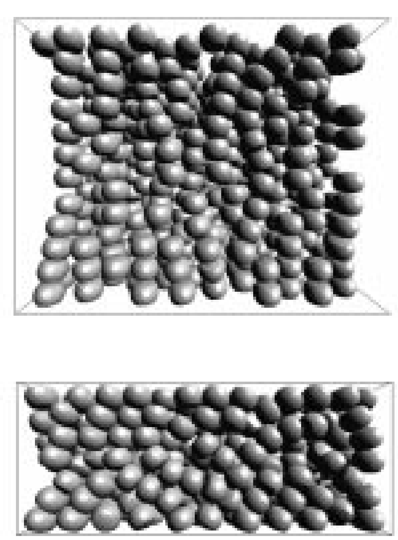

Fig. 6. Snapshots of particles in parallel compaction ($\rho_M = 0.25$).

For comparison, α is plotted for compaction without magnetic field in Fig. 5. Changes in α with density ratio are obviously quite different from those with magnetic field. In die compaction, the particles are inclined toward z direction, maybe because of the particles' shape. In the case of isostatic compaction, α is almost constant. This would be due to the facts that were mentioned previously for the case with magnetic field.

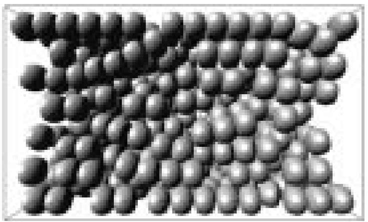

Fig. 7. Snapshot of particles in cross compaction at $\rho = 0.45 (\rho_M = 0.25)$.

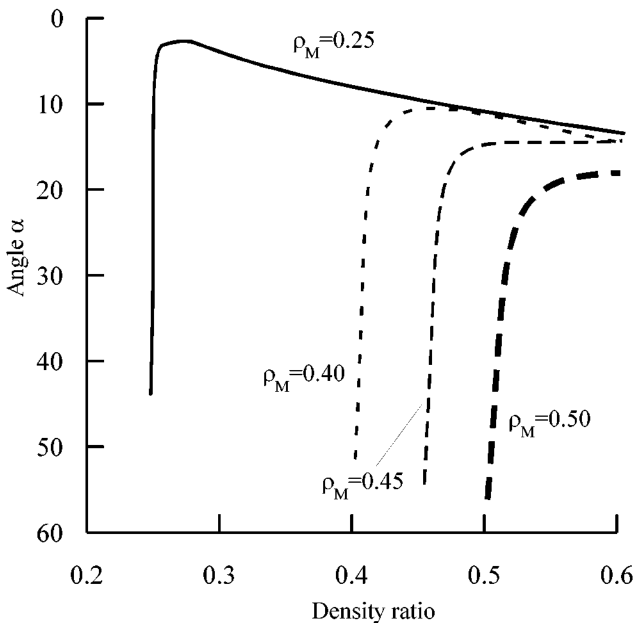

Fig. 8. Relationship between average angle α and density ratio during transverse compaction.

C. Effect of ρ_M on Alignment

The preceding results show that the anisotropy gives a large effect on the pressure and hence on the alignment of particles. We carried out PDM simulation of compaction in an applied magnetic field with various values of ρ_M. Fig. 8 shows changes in the average angle α with density ratio for various values of ρ_M. Angle α becomes very small just after the application of the magnetic field for any ρ_M, in particular when ρ_M is as low as 0.25. As compaction proceeds, the angle increases slightly. The result shows that the lower the value of ρ_M, the smaller is the final average angle α. The anisotropy on the whole was thus affected by the space around particles for rotation or rearrangement when the magnetic field was applied. Consequently, the performance of the obtained permanent magnet would be affected significantly by the value of ρ_M. These phenomena are observed in actual processes.

D. Discussion on Alignment and Performance of Magnet

The simulated results suggest that the magnetic performance of the obtained compact differs depending on the compaction type. We, therefore, measured the residual magnetic flux density of the sintered compacts, B_r, made by parallel and cross compaction at 8.00×10^5 [A/m]; the magnetic field was applied from $\rho = 0.25$. The density ratio of the compacts after compaction was 0.56-0.57, and after sintering it was almost 100%. The residual magnetic flux of the powder, B_0, was 1.4335 [Wb/m^2], while it was 1.362 ($B_r/B_0 = 0.95$) and 1.254 [Wb/m^2] ($B_r/B_0 = 0.875$) for the compacts obtained by cross and parallel compaction, respectively. The calculated average angle, α, by the simulation is about 15 degree for transverse compaction and 40 degree for parallel compaction (see Fig. 5). We are not able to calculate the residual magnetic flux density from the average angle, the tendency agrees with the above experimental result. The angle after parallel compaction seems to be larger comparing with the residual magnetic flux density of the sintered compact ($B_r/B_0 = 0.875$). This may be due to the particle model employed for the present simulation; we are now trying to investigate the effect of particle size distribution on the alignment and the size distribution seems to give a large influence on it. This should be studied further in detail.

V. Conclusions

We simulated the alignment of magnetic particles during compaction in magnetic field. The obtained results showed that compaction mode gave a great effect on the alignment, and that the higher the density ratio at which the magnetic field was applied, the worse was the alignment. The application of the magnetic field caused pressure difference during compaction in transverse directions. The pressure difference was attributed mainly to the structural anisotropy induced by the application of the magnetic field. Since we considered that the anisotropy, in turn, corresponds to magnetic alignment or performance of the obtained compacts, we measured the residual magnetic flux density of the sintered compacts. The results agreed qualitatively with simulated ones.

Acknowledgment

The authors would like to thank Dr. Kaneko and Mr. Kohara of Sumitomo Special Metals Co. Ltd. for their help in carrying out the experiments.

References

[1] Y. Kaneko and N. Ishigaki, "Technical Report," Sumitomo Metal Industries, Ltd., vol. 48, 1996.

[2] S. Hosokawa, S. Toyota, O. Yamashita, and K. Okimoto, "Influences of pulverized particle size and magnetic field during compacting on th degree of alignment of Sr-Ferrite," *J. Powder & Powder Metall.*, vol. 45, pp. 77–81, 1998.

[3] H. Kotera, H. Kitahara, and S. Shima, "Particle dynamics simulation for behavior of elliptical particles," *Adv. in Powder Met. and Particulate Materials-1996*, pp. 7–101, 1996.

[4] ——, "3-D simulation of magnetic particles' behavior during compaction in magnetic field," Powder Technology, to be published.

[5] ——, "A study of constitutive behavior of powder assembly by simulation with nonspherical particle modeling," *Proc. of the 1998 Powder Metallurgy World Congress and Exhibition*, vol. 2, pp. 240–245, 1998.