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Numerical simulation of magnetic-aligned compaction with pulsed high magnetic field

Rikio Soda *, Kenta Takagi, Kimihiro Ozaki

Green Innovative Magnetic Material Lab., Department of Materials and Chemistry, Inorganic Functional Materials Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Japan

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ABSTRACT

A three-dimensional discrete element method capable of handling ferromagnetic particles was developed to enable computer simulation of powder metallurgic processes for the production of bulk magnets, and was applied to the magnetic-aligned compaction process with a pulsed high magnetic field which we proposed. The simulation results showed that the pulsed-magnetic field causes a decrease in contact force due to particle rearrangement. This decrease was experimentally confirmed as a decrease in compaction pressure, thus verifying the developed simulation model is capable of predicting the motion peculiar to magnetic particles.

Magnetic-aligned powder molding processes such as powder compaction and mold injection are important processes for maximizing the performance of raw magnetic powders in the manufacture of anisotropic bulk magnet products. In a magnetic-aligned compaction process, an essential requirement for obtaining a magnet with a high orientation of magnetization along the easy axis is to apply a sufficiently high magnetic field exceeding the coercive force of the raw powder. However, the coercivity of recently developed magnetic powders, such as HDDR-processed powders and ultrafine powders [1], is greater than the magnetic fields which can be obtained with ordinary electromagnets. Therefore, an alternative technique must be developed in order to prepare highly oriented green compacts. We believed that a computer simulation using the discrete element method (DEM) might provide a deep understanding of particle motion in magnetic-aligned processes, and this would be a significant aid for the development for a new magnetic-aligned process [2]. To date, some reports have demonstrated that DEM simulations enable visualization of the motion of particles in a magnetic-aligned process [3–8]. However, the conventional DEM simulation models were insufficient for accurate determination of the motion of permanent magnetic particles because they ignored the magnetically hysteretic property of those particles. Because permanent magnet particles have residual magnetization if once exposed to an external magnetic field, the interaction of residual magnetization between neighboring particles may change the position and orientation of the particles after the magnetic field is removed. Therefore, it is necessary to develop a new simulation model which considers magnetic hysteresis.

A pulsed-magnetic field generated by a capacitor-type magnetizer is one candidate solution for producing anisotropic green compacts of powders having huge coercivity because it can easily and inexpensively provide a very strong magnetic field over 3 T. However, due to the short pulse duration of <0.1 s, it is necessary to develop a different technique from the conventional process, which uses a static magnetic field. Our target simulation model is thought to be suitable for understanding the instantaneous motion of the magnetic particles under a pulsed-magnetic field. Therefore, the aim in this study was to develop a new three-dimensional DEM simulation technique for analysis of the motion of magnetic particles with magnetic hysteresis in order to visualize the particle motion in the magnetic-aligned compaction process with a pulsed-magnetic field, and to discuss the possibility of this process based on the simulation results.

This study targeted a simple model of uniaxial compaction with a cylindrical die set. The pulsed-magnetic field is assumed to be applied parallel to the pressing direction. In the DEM, the translational and rotational motions of each particle are considered separately, as shown in Eq. (1) [9].

$$\begin{aligned} a &= \sum (\boldsymbol{F}_{\mathrm{c}}^{\mathrm{n}} + \boldsymbol{F}_{\mathrm{c}}^{\mathrm{t}} + \boldsymbol{F}_{\mathrm{m}})/m + \boldsymbol{g} \\ \alpha &= \sum (\boldsymbol{M}_c + \boldsymbol{M}_m)/I \end{aligned} \quad (1)$$

where a, α, m, g and I are the acceleration, angular acceleration and mass of a particle, gravitational acceleration and the moment of inertia, respectively. The components of the normal and tangential contact forces $\boldsymbol{F}_{\mathrm{c}}^{\mathrm{n}}$ and $\boldsymbol{F}_{\mathrm{c}}^{\mathrm{t}}$ are modeled based on the Voigt model. The magnetic force and

* Corresponding author at: 2266-98 Anagahora, Shimo-Shidami, Moriyama-ku, Nagoya, Aichi 463-8560, Japan.
E-mail address: r-soda@aist.go.jp (R. Soda).

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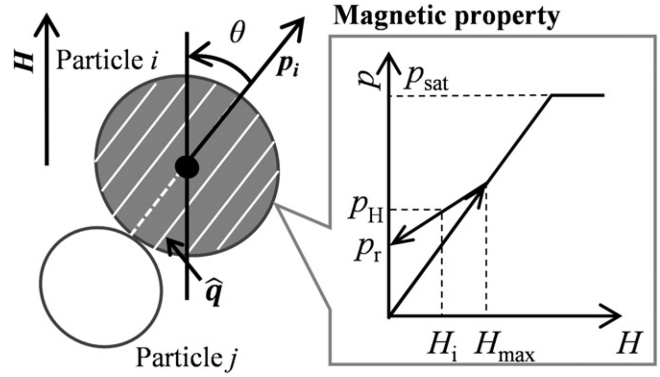

Fig. 1. Schematics of calculation model and conditions. The inset at the right represents the generalized magnetic hysteresis used in the calculations.

the moment, $\boldsymbol{F}_{\mathrm{m}}$ and $\boldsymbol{M}_{\mathrm{m}}$, respectively, are calculated by the following equations [10,11].

$$\begin{aligned} \boldsymbol{F}_{\mathrm{m}} &= (\boldsymbol{p_i} \cdot \nabla)\boldsymbol{B_i} \\ \boldsymbol{M}_{\mathrm{m}} &= \boldsymbol{p_i} \times \boldsymbol{B_i} \end{aligned} \tag{2}$$

where $\boldsymbol{p_i}$ is the magnetic moment and $\boldsymbol{B_i}$ is the magnetic flux density acting on the i-th particle. As mentioned above, an accurate evaluation of the magnetic moment p_i is one of the important factors. Therefore, we propose a simulation model that can represent the magnetic hysteresis of particles. The magnetic hysteresis of the particles is defined as illustrated schematically in Fig. 1. The magnetic moment p_i can be calculated from the following equation using the maximum value of the applied magnetic field $H_{\max}$ and the current value of the magnetic field H_i:

$$\begin{cases} \boldsymbol{p}_i = \min(p_{\mathrm{sat}}, p_H(\theta, H_{\max}))\hat{\boldsymbol{q}}, & H_{\mathrm{i}} < H_{\max} \\ \boldsymbol{p}_i = \min(p_{\mathrm{sat}}, \chi H_i)\hat{\boldsymbol{q}}, & H_i \geq H_{\max} \end{cases} \tag{3}$$

where p_{sat}, χ, θ and $\boldsymbol{q}$ are the saturation magnetic moment, the average magnetic susceptibility of the initial magnetization curve, the angle between the easy axis and the magnetic field and the direction (unit vector) of the easy axis, respectively. As shown in Fig. 1, the minor loop $\boldsymbol{p}_{\mathrm{H}}$ from $H = 0$ to $H_{\max}$ was linearly approximated as follows:

$$\boldsymbol{p}_{\mathrm{H}} = \frac{\chi H_{\max} - \boldsymbol{p}_{\mathrm{r}}(\theta, H_{\max})}{\boldsymbol{H}_{\max}} \boldsymbol{H}_i + \boldsymbol{p}_{\mathrm{r}}(\theta, H_{\max}) \tag{4}$$

where $\boldsymbol{p}_{\mathrm{r}}(\theta, H_{\max})$ is the residual magnetic moment on a particle that was once exposed to a magnetic field of $H_{\max}$. The residual magnetization $\boldsymbol{p}_{\mathrm{r}}$ is approximated by the following equation.

$$\boldsymbol{p}_{\mathrm{r}}(\theta, H_{\max}) = \boldsymbol{p}_{\mathrm{r,\,max}}\left(H_{\max}^n / \left(k^n + H_{\max}^n\right)\right) \tag{5}$$

where $\boldsymbol{p}_{\mathrm{r,max}}$ is the maximum value of the residual magnetic moment, which is obtained from the major hysteresis loop. The fitting parameters n and k were determined from the measured results of the minor loop. In this study, $\boldsymbol{p}_{\mathrm{r,max}}$, n and k were experimentally determined by using a vibration sample magnetometer as $1.075 \times 10^6 - 4.961 \times 10^5\theta$,$7.033 \times 10^5 - 3.188 \times 10^6 \exp(\theta/0.482)$ and $2.821 - 1.817 \times 10^{-4} \exp(\theta/0.179)$ (Coefficient of determination, adjusted $R^2 > 0.99$). The waveform of the pulsed-magnetic field was defined as the following empirical equation in this study:

$$\boldsymbol{H} = 4.9\left(1 - \exp\left(-t/2.5 \times 10^{-4}\right)^{3.48} \exp(-t/0.01)\right) \tag{6}$$

A commercially available Nd-Fe-B permanent magnet powder (MAGFINE 15P, Aichi Steel Co.) was chosen as the model powder. The Young's modulus, Poisson's ratio, Coefficient of restitution, Coefficient of friction, density and saturation magnetic moment of this powder, which were required for the simulation, were 150 GPa, 0.3, 0.0, 0.75, 7500 kg/m^3 and 1114 kA/m, respectively [2]. The particle size distribution used for the simulation was approximated to 4.95 in log mean deviation and 0.530 in log-standard deviation as the lognormal distribution from the experimental result measured by laser diffractometry (adjusted $R^2 = 0.983$). In order to reduce the computation time, the numerical analysis was performed for a small region of the green compact that contained a thousand particles.

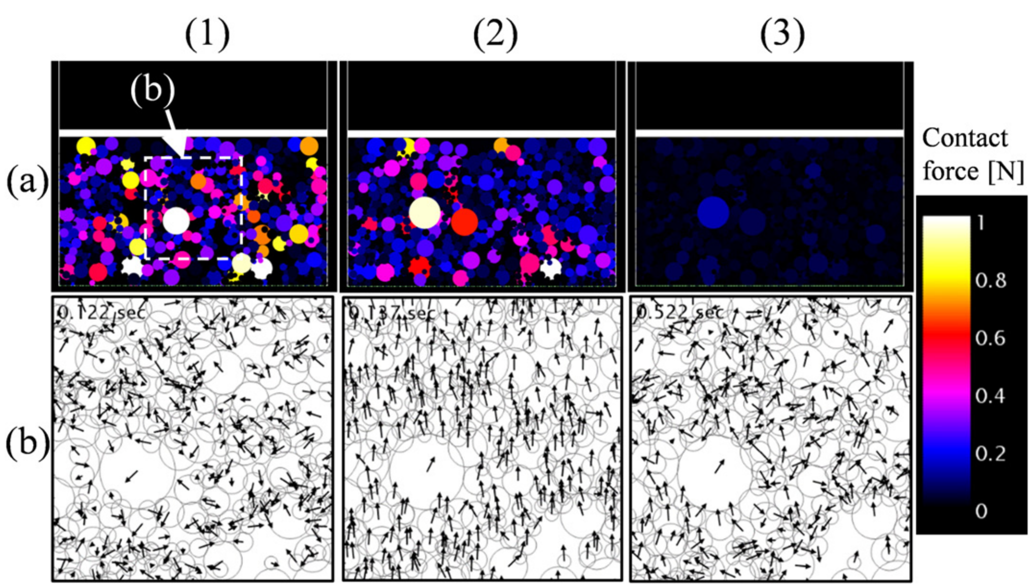

Fig. 2. Snapshots of particle motion at various times in magnetic-aligned compaction with the pressure of 2.5 MPa. The configurations of particles after (1) applying pressure, (2) applying a pulsed-magnetic field and (3) removing the pulsed-magnetic field. The white horizontal line indicates the bottom of the upper punch, and (a) and (b) represent the contact forces and the particle orientation, respectively. Contact force is represented by color and orientation is represented by arrows.