Powder Technology 329 (2018) 364–370

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Simulation-aided development of magnetic-aligned compaction process with pulsed magnetic field

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ARTICLE INFO

Article history:
Received 18 July 2017
Received in revised form 25 October 2017
Accepted 18 January 2018
Available online 02 February 2018

Keywords:
Discrete element method
Magnetic-aligned compaction process
Permanent magnet
Pulsed magnetic field
Particle orientation

ABSTRACT

In order to develop a new magnetic-aligned compaction process using a pulsed magnetic field for the most recent high performance magnetic powder and to understand the mechanism of particle orientation behavior in the magnetic field, visualization of particle motion and prediction of the degree of alignment were performed by using a three-dimensional particle-based simulation method developed by the authors. This simulation study revealed that the degree of alignment changed significantly in a time on the order of milliseconds during the application of the pulsed magnetic field. Furthermore, preparation of a highly oriented green compact required millisecond-level synchronization control of the application of the pulsed magnetic field and the compacting action. Based on the simulation results, a magnetic-aligned compacting apparatus capable of synchronizing the application of the magnetic field and the compacting action with accuracy on the order of milliseconds was developed. As a result, the optimum aligned condition in experiments and the simulation was consistent. By using the proposed synchronization method, the degree of alignment was improved and the maximum magnetic energy product was increased by about 9% and 15%, respectively, compared with the conventional method.

1. Introduction

Higher performance sintered permanent magnets are required because this type of magnet is an important part for determining the performance of IPM (Interior Permanent Magnet) motors used in hybrid/electric vehicles and eco-friendly electrical appliances. Sintered permanent magnets are generally produced by a powder metallurgical approach. Fine powders are first prepared by pulverizing raw ingots or coarse powders, and the powders are then compacted in a magnetic field to obtain green compacts in which the easy axis of magnetization is highly oriented. The green compacts are densified by sintering while keeping the easy axis orientation. Among these processes, magnetic-aligned compaction is important for maximizing the magnetization of the magnetic powder to the final sintered magnets. However, in recent years, magnetic-aligned compaction has become increasingly difficult due to the development of finer and high coercive permanent magnet powders. For example, ultrafine powders require a higher magnetic field to overcome interparticle frictional forces, and powders with high coercive force, such as HDDR-processed powders, require a higher applied magnetic field over the necessary magnetic field applied to the magnetized powder for orientation [1]. The most straightforward approach to solve these problems would be the use of a superconducting magnet, which is able to supply static magnetic fields of >10 T, instead of an electromagnet. However, application of superconducting magnets for this purpose is impractical because of the very high cost and large size of the apparatus, as well as the use of a liquid helium coolant. Therefore, we focused on the pulsed magnetic field as an accessible method for preparing highly oriented green compacts from the most recent high performance magnetic powder. The pulsed magnetic field that is produced by a brief moment of emission of a huge electric charge from a capacitor bank is capable of supplying a strong magnetic field comparable to that of superconducting magnets. Nevertheless, the apparatus that produces the pulsed magnetic field has a simple construction, consisting of a capacitor bank and an air core coil, which means the cost is considerably lower than that of a superconducting magnet. It is for this reason, for example, that aligned compaction using a pulsed magnetic field has been applied to ultrafine Nd-Fe-B powder prepared by pulverizing using a He gas jetmill [2,3]. On the other hand, whereas superconducting magnets and electromagnets can supply a static magnetic field, that is to say, there is no limit on the duration of the magnetic field, the pulsed magnetic field has a limited duration. In general, the duration of a pulsed magnetic field is limited to less than about 50 milliseconds. Our previous studies have shown that highly oriented green compacts could not be obtained when compacting was performed after application of a pulsed

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https://doi.org/10.1016/j.powtec.2018.01.035
0032-5910/

magnetic field because the particles oriented in the direction of the magnetic field were rotated by the local magnetic field generated by the remanent magnetization [4]. Therefore, we are developing an alternative orientation technique that makes it possible to obtain highly oriented green compacts by using a pulsed magnetic field. In order to realize highly oriented green compacts by using a pulsed magnetic field, an understanding of the motion of the magnet powder in the magnetic field is required. However, experimental observation of particle motion in a pulsed magnetic field is extremely difficult because the magnitude of the magnetic field changes significantly in a time on the order of milliseconds.

Therefore, we are also developing a simulation technique which is capable of visualizing particle motion in a magnetic field. The discrete element method (DEM) is used in this simulation of magnetic particles because it enables comprehensive visualization of the movements of individual particles, which is quite difficult with analytical techniques based on continuous body dynamics, such as the finite element method [5–12]. To date, there have been some reports in which the motions of magnet particles were analyzed by DEM, but those studies did not consider remanence. As mentioned above, remanence is one of the important factors that causes misorientation of oriented magnetic particles. Our proposed simulation model can consider magnetic hysteresis and crystal magnetic anisotropy. Our previous study verified the reliability of this simulation model by comparison with experimental results, and suggested the possibility of producing highly oriented green compacts by optimizing the process conditions [4,13].

In particular, the analytical results implied that synchronization control of the application of the magnetic field and the compacting load is very important for obtaining a high orientation. Therefore, in the present study, our aim is to analyze the influence of the delay between pressurization of the compact and application of the magnetic field on the degree of alignment by using the developed simulation model. In addition, we also designed and assembled a magnetic-aligned compacting apparatus based on the analysis results so as to realize the optimum alignment conditions, and attempted to produce highly oriented green compacts.

2. Simulation methodology

In the simulation model used in this study, all the particles were modeled as elastic spherical particles with various particle sizes. Plastic deformation and breakage of particles was not considered. In practice, most of permanent magnetic materials such as Nd-Fe-B present non-plasticity. All the particles translate and rotate as a result of the forces acting on each particle. The contact forces acting on the individual permanent magnet particles were viscoelastic force, frictional force, gravitational force and magnetic force [14]. When a particle is in contact with $\boldsymbol{n}_\mathrm{c}$ particles and interacts magnetically with $\boldsymbol{n}_\mathrm{m}$ particles, the force $\boldsymbol{F_i}$ and moment $\boldsymbol{M_i}$ acting on the i-th particle are calculated by using the following equation.

$$\boldsymbol{F}_i = \sum_{j=0}^{n_c} \boldsymbol{F}_{\mathrm{contact},ij} + \sum_{k=0}^{n_m} \boldsymbol{F}_{\mathrm{magnetic},ik} + m_i\boldsymbol{g} \tag{1}$$

$$\boldsymbol{M}_i = \sum_{j=0}^{n_c} \boldsymbol{M}_{\mathrm{contact},ij} + \sum_{k=0}^{n_m} \boldsymbol{M}_{\mathrm{magnetic},ik} \tag{2}$$

where, $\boldsymbol{F}_{\mathrm{contact},\ ij}$ and $\boldsymbol{M}_{\mathrm{contact},\ ij}$ are the contact force and moment acting between particles i and j, and $\boldsymbol{F}_{\mathrm{magnetic},\ ik}$ and $\boldsymbol{M}_{\mathrm{magnetic},\ ik}$ are the magnetic force and moment acting between particles i and k, respectively. The calculation method for the contact force $\boldsymbol{F}_{\mathrm{contact},\ ij}$ and moment $\boldsymbol{M}_{\mathrm{contact},\ ij}$ basically follows previous studies [4,13] (see Appendix A). The magnetic dipole was modeled as the vector at the barycentric position of the particle. In order to model the crystal magnetic anisotropy of the permanent magnet, it is assumed that an easy axis of magnetization exists in each particle [15,16].

$$\boldsymbol{F}_{\mathrm{magnetic}} = (\boldsymbol{p}_i \cdot \nabla)\boldsymbol{B}_i(\boldsymbol{x}_i) \tag{3}$$

$$\boldsymbol{M}_{\mathrm{magnetic}} = \boldsymbol{p}_i \times \boldsymbol{B}_i(\boldsymbol{x}_i) \tag{4}$$

where, $\boldsymbol{B}_i(\boldsymbol{x}_i)$ and $\boldsymbol{p}_i$ are the magnetic flux density at the position of the i-th particle and the magnetic moment of the i-th particle, respectively. The magnetic flux density of the i-th particle is calculated from the sum of the external magnetic flux density at the i-th particle position $\boldsymbol{B}_{i,\ \mathrm{ext}}$ and the magnetic flux density generated by the interaction between particles i and k.

$$\boldsymbol{B}_i(\boldsymbol{x}_i) = \boldsymbol{B}_{i,\ \mathrm{ext}} + \frac{\mu_0}{4\pi}\sum_{k=0}^{n_m}\left(\frac{3(\boldsymbol{p}_k \cdot \boldsymbol{r}_{ik})}{|\boldsymbol{r}_{ik}|^5}\boldsymbol{r}_{ik} - \frac{\boldsymbol{p}_k}{|\boldsymbol{r}_{ik}|^3}\right) \tag{5}$$

The waveform of the external pulsed-magnetic field was used as the following equation:

$$|\boldsymbol{B}_{\mathrm{ext}}| = 1.3828 B_{\mathrm{peak}}\left(1 - \exp\left(-t/1.12 \times 10^{-3}\right)\right)^{1.648} \exp(-t/0.018) \tag{6}$$

where, B_{peak} is peak magnitude of external magnetic field.

In simulations of permanent magnet particles, an accurate evaluation of the magnetic moment considering magnetic hysteresis is important for predicting the particle motion in the pulsed magnetic-aligned compaction process. Therefore, the magnetic moment $\boldsymbol{p_i}$ was calculated from the following equation by using the maximum value of the applied magnetic field $H_{i,\ \max}$ and the current magnitude of the magnetic field at the position of the i-th particle $H_i(\boldsymbol{x}_i)$ that can represent magnetic hysteresis [4]:

$$\begin{cases} \boldsymbol{p}_i = \min(p_{\mathrm{sat}}, p_H(\theta_i, H_{i,\ \max}))\hat{\boldsymbol{q}}, & |\boldsymbol{H_i}(\boldsymbol{x_i})| < H_{i,\ \max} \\ \boldsymbol{p}_i = \min(p_{\mathrm{sat}}, \chi H_i(\boldsymbol{x}_i))\hat{\boldsymbol{q}}, & |\boldsymbol{H_i}(\boldsymbol{x_i})| \geq H_{i,\ \max} \end{cases} \tag{7}$$

where, p_{sat}, χ and $\hat{\boldsymbol{p}}$ are the saturation magnetic moment, the average magnetic susceptibility of the initial magnetization curve and the direction of the easy axis, respectively. The misorientation of the i-th particle $\theta_{\boldsymbol{i}}$ can be calculated by the following equations from the angle between the magnetic field $H_{i,\ \max}$ and the direction of the easy axis.

$$\theta_i = \cos^{-1}\left(\frac{\boldsymbol{H} \cdot \hat{\boldsymbol{q}}_i}{|\boldsymbol{H}||\hat{\boldsymbol{q}}_i|}\right) \tag{8}$$

p_H is a function of $\theta_{\boldsymbol{i}}$ and $H_{i,\ \max}$, which is a minor loop between the magnetic field of 0 to $H_{i,\ \max}$, and was calculated by following equation:

$$\boldsymbol{p}_{\mathrm{H}} = \frac{\chi(\theta)H_{i,\ \max} - \boldsymbol{p}_{\mathrm{r}}(\theta, H_{i,\ \max})}{H_{i,\ \max}}\boldsymbol{H_i}(\boldsymbol{x}_i) + \boldsymbol{p}_{\mathrm{r},\ \max}\left(H_{i,\ \max}^n \Big/ \left(s^n + H_{i,\ \max}^n\right)\right) \tag{9}$$

where, $\boldsymbol{p}_{\mathrm{r},\ \max}$ is the maximum value of the residual magnetic moment, and n and s are hysteresis parameters. $\boldsymbol{p}_{\mathrm{r},\ \max}$, n and s are experimentally determined by using a vibration sample magnetometer (VSM). The degree of alignment of a green compact can be calculated from the following equation by using the misorientation $\theta_{\boldsymbol{i}}$ and volume of the i-th particle V_i:

$$\alpha = \cos\left(\frac{\sum_{i=1}^{N}(\theta_i V_i)}{\sum_{i=1}^{N} V_i}\right) \tag{10}$$

where, N is the total number of particles constituting the green compact.

3. Experimental procedure

This study examined uniaxial compression molding with a pulsed magnetic field as described below. The powder was filled in a cylindrical die having a diameter of 10 mm, the upper punch was moved at a speed of 100 mm/s, and the powder was compacted at a compaction pressure