A Numerical Calculation Method for Forming Process of Resin Bond Magnet

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The forming process of the resin bond magnet involves the complex behaviors such as melting of resin, ferromagnetic powders movement under a magnetic field and granules behavior. Therefore, it is extremely difficult to control and design of such a process. As a one approach for the mentioned problems, the numerical calculation that simulate comprehensively the process is required. In this study, the Discrete Element Method, Method of Moments and Weighted Least Square Method are employed. This report provides an account of the coupled simulation method for forming process of resin bonding magnet.

***Index Terms*—Method of Moments, Discrete Element Method, Moving Particle Simulation Method, Numerical Modeling**

I. Introduction

THE FORMING process of the resin bond magnets consists of the complex phenomena such as melting of resin, granule movement under a magnetic field and thermal flow. Therefore, it is extremely difficult to the design of materials and control of behaviors ferromagnetic powders. There are some problems such as emergence of inhomogeneous characteristics (e. g. magnetization, density) of formed magnets reside in the forming process. In recent years, the calculation techniques for multi-physics phenomena as CAE technique have been proposed [1]-[2]. However, the models that are treated by these method are restricted to static problems. In this study, comprehensive simulation model of the forming process is proposed.

In this report, the Discrete Element Method (DEM) [3], the Method of Moments (MoM) [4] and the Weighted Least Square Method (WLSM) [5] are employed as granular movement analysis, magnetic field analysis and thermal flow analysis. The algorism of each methods and coupling method are described.

Also, the numerical model of resin coating powder by DEM is proposed. In the model, the ferromagnetic powders are covered with viscous region. The damping factor depends on the temperature.

II. Employed Analysis Methods

The forming process of resin bond magnets is consisted by melting of resin, granule movement under a magnetic field, thermal flow and compression of granules. In this paper, the coupling calculation method for this process is proposed.

The granules behavior is calculated by DEM. Collision between granules is modeled by Voigt model. The motion equations are as follows:

$$m\frac{d^2\boldsymbol{x}}{dt^2} + c\frac{d\boldsymbol{x}}{dt} + k\boldsymbol{x} = \boldsymbol{F} \tag{1}$$

$$I\frac{d^2\boldsymbol{p}}{dt^2} + cr^2\frac{d\boldsymbol{p}}{dt} + kr^2\boldsymbol{p} = \boldsymbol{T}. \tag{2}$$

The m is a mass, $\boldsymbol{x}$ is a displacement of element, c is a damping coefficient, k is a spring constant, $\boldsymbol{F}$ is external force, I is an inertia, $\boldsymbol{p}$ is a rotational displacement, r is a radius of element and $\boldsymbol{T}$ is torque. The contact force is calculated by an overlapping of the elements. Therefore, the overlapping of the elements is tolerated in DEM. Additionally, linear spring coefficient can be employed if the overlapping is sufficiently small.

Static magnetic field distribution is calculated by MoM. the integral equation about magnetization $\boldsymbol{M}$ is treated.

$$\frac{\chi_i}{4\pi}\sum_j\left[\nabla\int_V \boldsymbol{M}\cdot\nabla\left(\frac{1}{r_{ij}}\right)dV\right] + \boldsymbol{M}_i = \chi_i\mu_0\boldsymbol{H}_i \tag{3}$$

where, χ_i is the magnetic susceptibility of element i, $\boldsymbol{M}_i$ is the magnetization vector on element i, r_{ij} is the distance between ferromagnetic element i and j, V is the volume of element i, μ_0 is the permeability on free space and $\boldsymbol{H}_i$ is the external magnetic field strength. The equation just means the interactions between a ferromagnetic material element i and others. The magnetic force and torque per unit volume on certain element presented by

$$\boldsymbol{f} = \nabla(\boldsymbol{M}\cdot\boldsymbol{H}_e) + \frac{1}{2}\nabla(\boldsymbol{M}\cdot\boldsymbol{H}') \tag{4}$$

$$\boldsymbol{\tau} = \boldsymbol{M}\times(\boldsymbol{H}_e + \boldsymbol{H}'). \tag{5}$$

Here, $\boldsymbol{H}_e$ is the external magnetic field by source. $\boldsymbol{H}'$ is the external magnetic field by other elements. These terms assigned to the external force and torque term of Eqs. (1), (2). After this, velocity and position of each elements are updated.

Finally, the heat flow is calculated by the mesh-free method based on WLSM. The heat transfer equation is shown in Eq. (6).

$$\frac{DT}{Dt} = \frac{\kappa}{c\rho}\nabla^2 T + \frac{q}{c\rho} \tag{6}$$

where, T is the temperature, κ is the heat-transfer coefficient, c is the specific heat, ρ is the density and q is the internal heat generation. Then, the distribution of temperature is assumed as a second order polynomial function in WLSM. The approximate function of temperature as follows:

$$T_i(x,y,z) = \tau + a_1 x + a_2 y + a_3 z + a_4 x^2 + a_5 xy + a_6 y^2 + a_7 yz + a_8 z^2 + a_9 xz \tag{7}$$

where, T_i is the temperature at the calculation point i, a_k (k = 1~9)are the coefficients of the function and x, y, z are neighbor calculation points on a coordinate system with the origin at the coordinate of calculation point i. The Laplacian of T_i is presented by

$$\nabla^2 T_i = \frac{\partial^2 T_i}{\partial x^2} + \frac{\partial^2 T_i}{\partial y^2} + \frac{\partial^2 T_i}{\partial z^2} = 2(a_4 + a_6 + a_8)\cdot \tag{8}$$

III. Resin Model

In DEM process, the resin is modeled by using damping factor. The resin model is shown in Fig. 1. The particles are covered with a viscosity compartment. In this model, a viscous drag force is added to the each particles. The damping factor of viscous compartment depends on the temperature.

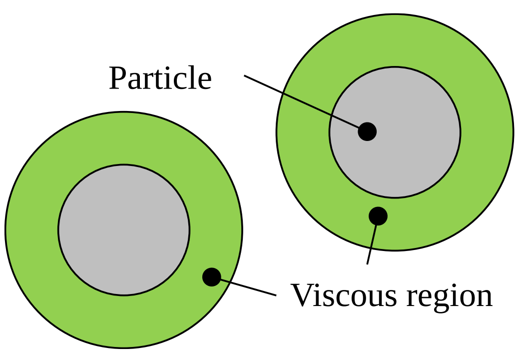

Fig. 1 Resin model.

TABLE I
ANALYSIS CONDITIONS

Parameter	Value
Number of elements	125
Permanent magnet magnetization [T]	0.3
Element diameter [mm]	0.4
Spring coefficient [N/m]	800
Density[kg/m^3]	7874
Coefficient of restitution	0.8
Dynamic friction coefficient	0.8
Relative permeability	3000
Time interval [s]	1e-06
Number of steps	500000

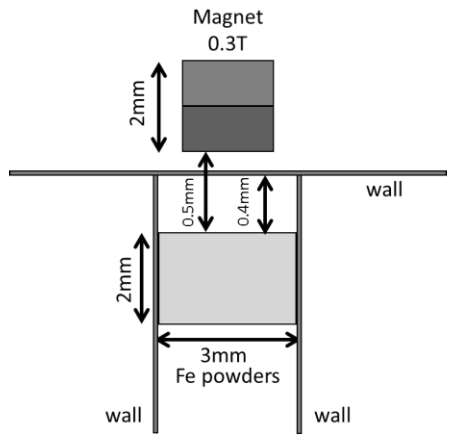

Fig. 2 Schematic analysis model.

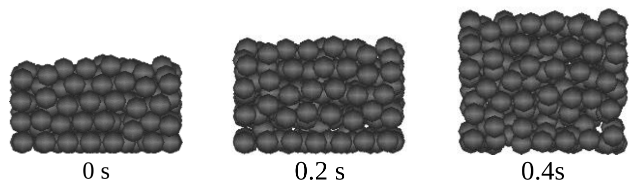

Fig. 3 Behavior of ferromagnetic powders under a magnetic field

IV. Analysis

In this section, the proposal method is applied to ferromagnetic powders under a magnetic field. The heat flow calculation result will be shown in full paper. The calculation conditions are shown in TABLE I. Also, the numerical model is shown in Fig. 2. The analyzed result are shown in Fig. 3. The ferromagnetic elements are attracted to the permanent magnet.

V.Conclusion

In this paper, the calculation technique for bonding process of resin bond magnet utilizing the Discrete Element Method, Method of Moments and Weighted Least Square Method is proposed. In extended paper, the coupling method, calculation result and experimental result are discussed at length.

References

[1] S. Noguchi et al. “Magnetic Field and Fluid Flow Computation Plural Kinds of Magnetic Particles for Magnetic Separation”, IEEE Trans. on Magn., Vol. 48, No.2, pp. 523-526, 2012.

[2] Yoshikawa, K. Hirata, F. Miyasaka and Y. Okaue “Numerical analysis of transitional behavior of ferrofluid employing MPS and FEM”, IEEE Trans. on Magn., vol. 48, no. 5, pp. 1379-1373, 2011.

[3] I. E. M. Severens, Discrete element method simulations of toner behavior in the development nip of the Océ Direct Imaging print process, Granular Matter, pp. 137-150, 2006.

[4] N. Takahashi, T. Nakata, N. Uchiyama, “Optimal design method of 3-D nonlinear magnetic circuit by using magnetization integral equation method”, IEEE Trans. on Magn., vol. 25, no. 5, pp4144-4146, 1989S.

[5] Matsuzawa, K. Mitsufuji, Y. Miyake, K. Hirata and F. Miyasaka, “Numerical Analysis of Electromagnetic Levitation Employing Meshless Method Based on Weighted Least Square Method”. J. Manufacturing Sci. & Production, pp. 29-24. 2015