Powder Technology 262 (2014) 198–202

Contents lists available at ScienceDirect

Powder Technology

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

# Rheological modeling of strontium ferrite feedstock for magnetic powder injection molding

Im Doo Jung [a], Sung Hun Kim [a], Seong Jin Park [a,*], See Jo Kim [b], Tae Gon Kang [c], Jang Min Park [d]

[a] Department of Mechanical Engineering, Pohang University of Science and Technology, San 31, Hyoja-dong, Nam-gu, Pohang 790-784, Republic of Korea
[b] Department of Mechanical Design Engineering, Andong National University, 1375 Gyeongdong-ro, Andong-si, Gyeongsangbuk-do 760-749, Republic of Korea
[c] School of Aerospace & Mechanical Engineering, Korea Aerospace University (KAU), 76, Hanggongdaehang-ro, Deoyang-gu, Goyang-si, Gyeonggi-do 412-791, Republic of Korea
[d] School of Mechanical Engineering, Yeungnam University, Gyeongsan 712-749, Republic of Korea

ARTICLE INFO

*Article history:*
Received 1 September 2013
Received in revised form 15 April 2014
Accepted 20 April 2014
Available online 29 April 2014

*Keywords:*
Powder injection molding
Magnetic PIM
Rheological modeling
Shear viscosity

ABSTRACT

Powder injection molding (PIM) is an important manufacturing technology for the net-shape production of metallic and ceramic components. PIM can also be a promising process for the mass production of magnetic parts. To mass produce magnetic components with complex shape and high performance through PIM, rheological behavior of the magnetic powder mixtures must be understood and characterized for various processing conditions. In the present study, we investigate the rheological behavior of strontium ferrite powder mixture affected by the shear rate, the temperatures, the external magnetic field, and the volume fraction of the powder. Several rheological models are employed to describe the shear viscosity of the mixture, which can be used for the design and optimization of the PIM process.



## 1. Introduction

Powder injection molding (PIM) is a productive and widely used technique for the net-shaping of metallic and ceramic components. This technique combines two conventional processes of injection molding process and powder metallurgy, producing high performance and high precision components with complex shape at a low cost [1]. PIM process consists of i) feedstock (powder–binder mixture) preparation; ii) injection molding; iii) debinding; and iv) sintering. Due to many advantages, PIM has been applied to produce various mechanical and biomedical components [2–5]. For example, mechanical components having three-dimensional complex shapes and/or microstructures such as precision actuator components and microsystem components can be produced by PIM process. Also PIM process has been applied to produce biomedical components such as medical tools for special surgical operations and dental components like orthodontic brackets.

PIM process can also be a promising process for a mass production of magnetic parts [6–9]. The magnetic PIM process enables a high precision replication of a magnetic part having geometrical complexity or micro-scale structures [7]. This technology can be directly applied to relevant manufacturing industries for production and commercialization of micro magnetic parts.

The magnetic performance of final product from magnetic PIM will be significantly affected by the orientation of the magnetic particles [10]. In this regard, magnetic field is commonly applied in the mold cavity during the injection process in order to align the magnetic particles with a designed direction [8]. The orientation behavior of the magnetic particles is determined by flow-particle interaction, particle–particle interaction and magnetic field–particle interaction. In order to characterize this complex behavior of the magnetic particles during injection process, one needs to understand the rheological behavior of the magnetic powder mixture under various conditions. Also a rheological modeling of the magnetic powder mixture is of particular importance for design and optimization of the process.

There have been several studies regarding the rheology of feedstock and its effect on PIM process. For example, homogeneity effects on feedstock viscosity for PIM were studied by German [11], and it was found that homogeneous mixing of the powder and binder results in the lowest viscosity of the feedstock. Zauner et al. [12] investigated the effect of feedstock viscosity on the dimensional accuracy of the injection molded green part in PIM process. It was noted that the temperature condition of the PIM process affects the dimensional accuracy of the molded part since the feedstock viscosity is significantly affected by the temperature. Wang et al. conducted numerical simulation for filling stage to understand the effects of mold dimensions on rheology of feedstock in micro powder injection molding [13]. He used a power law model and the Arrhenius type viscosity model to relate shear rate and temperature in the FEM simulation and found that PIM process parameters can be affected by the size of mold.

* Corresponding author. Tel.: +82 54 279 2182.
*E-mail address:* sjpark87@postech.ac.kr (S.J. Park).

http://dx.doi.org/10.1016/j.powtec.2014.04.073

Although there are several studies on the rheology as mentioned above, only few studies have been carried out on the rheology of magnetic powder mixture with particular emphasis on the effects of magnetic field, shear rate, temperature and powder volume fraction with regard to the PIM process. For example, Song [14] studied the rheological behaviors of Neodymium (Nd–Fe–B) powder mixtures for fabrication of bonded magnet, and rheological behavior was characterized by a simple rheological equation of state by nonlinear regression. Kim et al. [6] investigated the rheological behavior of strontium ferrite (Sr–Fe) feedstock for development of magnetic PIM process. In these studies, however, appropriate rheological modeling has not been carried out under magnetic field effect, which limits the application of their results to practical analysis of magnetic PIM process.

In this paper, we present a rheological modeling for Sr–Fe powder mixture based on experimental characterization the shear rheology of the mixture. The effects of magnetic field, shear rate, temperature and powder volume fraction are all investigated comprehensively by using rotational rheometer of plate–plate type. The shear viscosity of the mixture is modeled by employing several rheological models in order to describe the effects of all parameters mentioned above.

## 2. Rheological modeling

In general, the shear viscosity of the magnetic powder–binder mixture depends on the shear rate, particle shape and size, temperature, magnetic field flux density and powder volume fraction [6]. In this study of St–Fe feedstock, however, the effect of particle size and shape is found to be almost negligible thus it is not presented. The shear viscosity $\eta$ can be represented as follows

$$\eta(T,\dot{\gamma},\varphi,B) = \eta_0(T)S(\dot{\gamma})V(\varphi)M(B) \tag{1}$$

where $T$ is the absolute temperature, $\dot{\gamma}$ is the shear rate, $\phi$ is the powder volume fraction and $B$ is the magnetic flux density. $\eta_0$ is the zero-shear-rate-viscosity which depends on the temperature, and other functions of $S$, $V$ and $M$ represent the effects of $\dot{\gamma}$, $\phi$, and $B$, respectively.

The effect of temperature on shear viscosity is generally expressed by Arrhenius-type exponential equation [15].

$$\eta_0(T) = me^{\frac{Q}{RT}} \tag{2}$$

where $m$ is the material constant, $Q$ is the activation energy, $R$ is the universal gas constant (8.314 J mol$^{-1}$ K$^{-1}$).

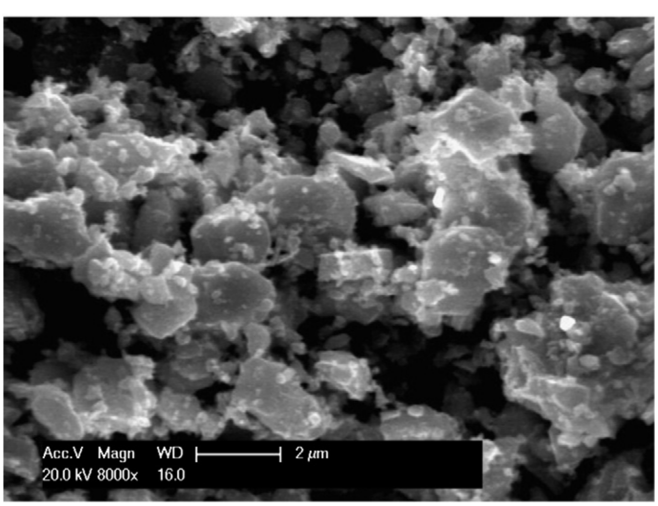


**Fig. 1.** SEM image of strontium ferrite powder.

**Table 1**
Magnetic properties of strontium ferrite powder.

| | |
|---|---|
| Composition | $SrO\cdot6Fe_2O_3$ |
| Type | Anisotropic |
| Residual magnetic flux density ($B_r$) | 0.4 T |
| Coercive force | 2800–3100 Oe |
| Intrinsic coercive force | 2900–3200 Oe |
| Maximum energy product | 3.5–4.0 MGOe |
| Average particle diameter | 2 μm |
| Pycnometer density | 5.17 g/cm$^3$ |

The most widely used form representing the shear rate dependency ($S$) of the viscosity is the power law model, which can be written as follows [16]

$$S = \dot{\gamma}^{n-1} \tag{3}$$

where $n$ is the flow behavior index. For a Newtonian fluid, the flow behavior index is unity, while shear thinning fluid like the present feedstock has the index less than unity.

As for the effect of powder volume fraction, there are many correlations reported in the literature [17–19]. In 1906, For infinitely dilute suspensions, Einstein developed an analytical model as follows

$$V = 1 + 2.5\phi. \tag{4}$$

Mooney had developed a phenomenological model by taking the packing state of particles into account as follows [17]

$$V = e^{\left(\frac{2.5\phi}{1-k\phi}\right)}, 1.35 < k < 1.91 \tag{5}$$

where $k$ is the crowding factor which represents the packing structure of particles. In this model, the particles are assumed to be spherical. The crowding factor is 1.35 when the packing state has a face-centered cubic (FCC) lattice structure, while the densest packing case of cubic packing has the crowding factor of 1.91, which is determined theoretically. For highly concentrated suspensions, Roscoe proposed the following model [18]

$$V = (1-1.35\phi)^{-2.5} \tag{6}$$

which is developed by expanding Einstein's model for dilute suspension to denser suspension case by taking the effects of aggregation and collision between particles into account. Krieger and Dougherty developed following model by introducing a maximum powder volume fraction [19]

$$V = \left(1-\frac{\phi}{\phi_m}\right)^{-2.5\phi_m} \tag{7}$$

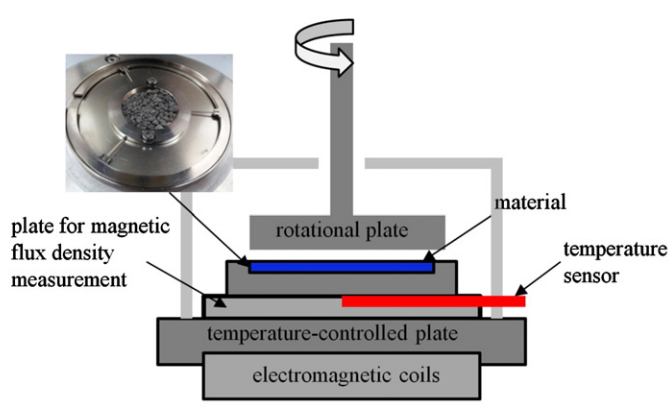


**Fig. 2.** Schematic diagram of rheometer.