Development of Electromechanical Principle for Wet and Dry Milling

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Abstract

The paper presents a novel electromechanical principle for wet and dry milling of different materials in which the milling beads are moved under time- and local-variable magnetic field. It is shown possibility to optimize the milling process in such milling machine by simulation of the gradient of vector electromagnetic field distribution in the working chamber. The mathematical model and simulation methods based on standard software packages are worked out. The results of numerical simulations and experimental measurements of electromagnetic field in working chamber of the developed and manufactured laboratory plant are in good correlation. With the obtained operating parameter dry milling experiments with crushed cement clinker and wet milling experiments of organic agents in the laboratory plant are executed and the results are discussed.

Introduction

Milling is an important but most complicated and energy consuming process in the production of materials. The interest of milling processes improvement in numerous industrial applications such as finest milling of pharmaceutical organic agents [1], raw materials for the ceramic, material for building industries [2] as well the recycling [3] have increased steadily. The relatively new electromechanical principle can be a solution for improvement of milling in numerous applications but still need methods and tools for the design and optimisation of milling machine.

The developed and manufactured laboratory plant has shown very good milling results [4]. Furthermore, the power consumption is very low as a result of direct power supplying to the grinding media. The biggest part, around 74 % of all supplied power in machine, is going to milling process and only 23 % to ohmic losses as well as 3 % to iron losses in the exciter systems [4].

The main parameter of such machine for milling (so-called EMZ plant) is the magnetic flux density and the resulting electromagnetic force distribution in the working chamber. For future development of this principle and design of new machine it is very important to develop a suitable model for numerical simulation of resulting electromagnetic force distribution and its optimization. The model is developed in ANSYS Maxwell and tested convergence on the calculation mesh, with different software setup and analysis type as well as different applied currents. Simulations are carried out in 2D and 3D. Verification done by comparing results in ANSYS Maxwell with COMSOL Multiphysics as well with experimental measurements of electromagnetic field in working chamber. With the obtained operating parameters dry milling experiments of crushing cement clinker and wet milling experiments of organic agents in the laboratory plant are executed. The results of milling experiments are discussed.
1. Electromechanical milling principle (EMZ)

The electromechanical milling principle is based on the moving of hard magnetic milling beads under the influence of the electromagnetic force $\vec{F}_{VB}$ generated by interaction between the vector gradient $\nabla \vec{B}$ of magnetic field $\vec{B}$ and the fixed magnetization $\vec{M}$ of the milling beads as shown in Fig. 1.

The generated force is given by (1):

$$\vec{F}_{VB} = (\vec{p}_M \cdot \nabla) \vec{B},$$

(1)

where $\vec{p}_M$ is the vector of the magnetic moment, given for milling beads by

$$\vec{p}_M = \int_{V} \hat{M} dV = \frac{1}{\mu_0} \int_{V} \hat{J} dV,$$

(2)

with $\hat{M}$ – the fixed permanent magnetization of the milling beads, $\hat{J}$ – its magnetic polarisation, $V$ – volume of a milling bead and $\mu_0 = 4\pi 10^{-7}$ Vs/Am – absolute permeability.

With the simplifying assumptions that the magnetization of the milling bead is $\vec{M} = \text{const.}$ in its volume and directed in the same direction as $\nabla \vec{B}$ we can deduce (3) for description of the electromagnetic force density $\vec{f}_{VB}$ on one milling bead:

$$\vec{f}_{VB} = \frac{\vec{F}_{VB}}{V} = \frac{\vec{M}}{V} \cdot (\nabla \vec{B}) = \frac{1}{\mu_0} \hat{J} \cdot (\nabla \vec{B}),$$

(3)

with $\vec{M}$ – magnitude of $\vec{M}$ and $\hat{J}$ – magnitude of $\vec{J}$.

As revealed in (3) the gradient of vector magnetic field $\nabla \vec{B}$ dictates the direction of the force density $\vec{f}_{VB}$ and the product $\hat{J} \cdot (\nabla \vec{B})$ determines their magnitude.

Additionally, if the magnetic vector gradient is time- and local-dependent, than a time- and local-dependent force density distribution $\vec{f}_{VB}(r, \varphi, z, t)$ is generated in the working chamber, consequently an intensive relative movement between several milling beads is induced which different types of mechanical stresses so that the novel electromechanical milling principle can be used for disintegration of biomass, dry or wet grinding of raw materials and autogenously grinding of ferrites [4, 5].

The principle scheme of the developed and manufactured electromechanical milling laboratory plant EMZ-LAI is presented in Fig. 2. The milling process room is an annular gap chamber made of non-ferromagnetic materials surrounded internal and external with a rotationally symmetrical exciter systems which generate a rotating magnetic field $\vec{B}(r, \varphi, z, t)$. The designs of the exciter systems are analogical to AC motor but with large air gap between outer (ESI) and inner (ESII) exciter systems (Fig. 3).
2. Model for calculation of the electromagnetic design

The electromagnetic design of EMZ machine is based on consideration of (3) and following important steps:

a) determination of the required gradient of vector magnetic field distribution $\nabla \vec{B}$ in the air gap with an existing EMZ plant and

b) determination of new design with the lowest possible losses at the required gradient $\nabla \vec{B}$.

For the determination of the vector gradient distribution $\nabla \vec{B}(r,z,\varphi,t)$ it is necessary to simulate the magnetic field distribution $\vec{B}(r,\varphi,z,t)$ in the air gap by (4)

$$\vec{B} = \text{rot}\vec{A} \text{ and } \text{div}\vec{B} = 0,$$

where $\vec{A}$ is the magnetic vector potential resulting from the design of the windings and electric current distribution in the exciter systems. Then $\nabla \vec{B}(r,z,\varphi,t)$ is calculable by (5):

$$\nabla \vec{B} = \left( \frac{\partial B_r}{\partial r} + \frac{\partial B_z}{\partial \varphi} + \frac{\partial B_\varphi}{\partial z} \right) \hat{e}_r + \left( \frac{\partial B_\varphi}{\partial r} + \frac{\partial B_z}{\partial \varphi} + \frac{\partial B_r}{\partial z} \right) \hat{e}_\varphi + \left( \frac{\partial B_r}{\partial r} + \frac{\partial B_\varphi}{\partial \varphi} + \frac{\partial B_z}{\partial z} \right) \hat{e}_z$$

The losses in the exciter systems of a EMZ plant are calculated as sum of core loss $P_{v,U}$ in its laminated cores and ohmic loss $P_{v,R}$ in the coils

$$P_v = P_{v,R} + P_{v,U},$$

with

$$P_{v,R} = \frac{1}{2\sigma} \int \bar{j}^2 dV,$$

where $\sigma$ is the electrical conductivity of the coils, $\bar{j}$ is the current density distribution in the windings and $V_v$ is winding volume and

$$P_{v,U} = \int_{V_v} \left( K_h \cdot f \cdot \vec{B}^2 + K_c \cdot \left( f \cdot \vec{B} \right)^2 + K_c \cdot \left( f \cdot \vec{B}^1.5 \right) \right) dV,$$
where \( f \) is the frequency of the electric currents in the coils of the windings, \( \hat{B} \) are values of the peak magnetic flux density in the exciter systems, \( V_{lc} \) is the volume of laminated cores, \( K_h \) is the hysteresis loss coefficient, \( K_i \) is the eddy current loss coefficient and \( K_h \) is the excessive loss coefficient. These coefficients are known from the data of iron sheets producer.

To build a model for simulation of electromagnetic field in ANSYS Maxwell it is necessary to include the design of the laminated cores and the coils distribution of the inner and outer systems of the EMZ plant. Fig. 3 shows an example of usable laminated cores and coils distribution as well as its electric connection (see Fig. 4).

The main geometrical parameters are outer diameter 322 mm and air gap width 25.5 mm. The number of slots of outer system is 48 and inner – 36.

Symmetrical time-dependent current distributions according to the phase connection are presented by following equations:

\[
i_A = I \cos(\omega t), \quad i_B = I \cos(\omega t - \frac{2\pi}{3}), \quad i_C = I \cos(\omega t - \frac{4\pi}{3})
\]  

(9 a, b, c)

To work out suitable for simulation model it is necessary to make the following tests:
- testing the size of model outer space,
- convergence on the calculation mesh,
- testing of different software setup and analyses type,
- simulation for different parameters,
- simulation in 2D and 3D,
- comparing simulation in ANSYS Maxwell and COMSOL Multiphysics,
- verification by experimental data.

The calculation domain split into elements uneven:
- parts in the exciter systems with large gradient of electromagnetic parameters, here the sizes of the cells are very small and
- in outer space with small gradient of electromagnetic parameters, here the size of elements increase.

The mesh convergence presented in [6] as dependency of error from finite element number results that the error is only 1.78 % at element number of 13258. This result is suitable for simulation and all further simulations are carrying out with this number of elements.
3. Results of the numerical simulations

The simulations of electromagnetic parameters are realized for following typical magnetic field strengths in air gap of $H_δ = 50$, 70 and 100 kA/m with a frequency of the electric currents of $f = 50$ Hz.

To verify the obtained simulation results the experimental measurement of magnetic flux density distribution in the middle of the air gap is carried out with the help of Hall Probe MNT-4E04-VH (Lake Shore) and Gauss meter 421 (Lake Shore). The results of these experimental measurements were compared with simulation data for the azimuthal and radial components. The relative differences amount maximal up to 7 %. This difference comes from influence of the real magnetic properties and geometry of the iron sheets, also from the discretization of the coil distribution.

The differences of magnetic flux density magnitude $B_{\text{mag}}$ obtained in ANSYS Maxwell and COMSOL Multiphysics are approximately 3 %. The differences between results in 2D and 3D simulation in all parameters distribution in the middle cross section arise 2-3 %. The results of all comparisons attest that the developed numerical model is possible to carry out in 2D and applicable for the electromagnetic design of exciter systems for electromechanical mills.

Fig. 5 presents the radial and azimuthal component of gradient of vector magnetic field in the air gap of the manufactured EMZ plant on three circles which are located in the near inner exciter system (R1), middle (R8), and outer exciter system (R16) of the air gap at $H_δ = 70$ kA/m and $f = 50$ Hz.

As can be seen the components of the gradient of vector magnetic field have same order up to 8 T/m, but their changes are larger close to the exciter systems (circle R1 and R16) than in the center of the air gap (R8). Consequently, the milling beads are more accelerate or brake close to the exciter systems. Here the movement changes are maximal.

In the center of the air gap the distribution is approximately sinusoidal along the circle R8. However, they are shifted, so that the azimuthal component $\nabla B_ϕ$ is larger where the radial component $\nabla B_r$ is smaller respectively inversely.

Other simulations [4] show that the magnitudes of the vector gradient components increase with the enhancement of the magnetic field strength $H_δ$ in the air gap and the number of poles $2p$ as well as with the reduction of the number of slots per pole per phase ($q \to 1$) and of the chording of the windings ($\varepsilon \to 0$). These are the potential for further improvements of the performance of mills based on the electromechanical principle [7].
4. Dry and wet milling in developed laboratory plant

To check this approach experiments in the laboratory installation (EMZ-LAI) with crushed cement clinker (dry milling) and anthraquinone (wet milling) are performed in dependent on the magnetic field strength $H_\delta$ at constantly current frequency and fillings rates of the working chamber.

In Fig. 6 the specific energy consumption $w_0$ of EMZ-LAI dependent on the milling ratio $z$ is presented in comparison with a ball mill (Bond) and a stirred ball mill (RWKM) at the same educt (cement clinker < 500 μm).

It is clearly derivable that the specific energy consumption of the EMZ-LAI is lower than $w_0$ of Bond and RWKM at the same milling ratio $z$ (e.g. $z = 4$). The larger the required milling ratio of the product must be, the larger is the energetic advantage of EMZ principle. Furthermore it is only possible to achieve a high fineness (e.g. $z = 7$) with the EMZ principle.

Fig. 7 demonstrates the milling progress of a special aqueous model fluid with contents of 5 wt-% anthraquinone particles (A90004-250G, Sigma-Aldrich Chemie GmbH / Taufkirchen) by increasing of the magnetic field strength $H_\delta$. The results of the experiments show that the anthraquinone particle are electromechanically grinded to $d_{50,3} < 1$ μm.

The realization of larger milling ratios requires smaller milling beads (< 1 mm).

**Fig. 6.** Specific energy consumption $w_0$ dependent on the milling ratio $z$ of EMZ-LAI – compared with a ball mill (Bond) and a stirred ball mill (RWKM) for dry milling of cement clinker with $d_o = 500$ μm

**Fig. 7.** Particle sizes $d_{10,3}$, $d_{50,3}$, $d_{90,3}$ dependent on the specific energy consumption $w_\delta$ for wet milling of anthraquinone with $d_{50,3} = 25.5$ μm

**Summary**

The methods and approaches for numerical simulation of magnetic field and its vector gradient in the ANSYS Maxwell and COMSOL Multiphysics are worked out. It is shown possibility to check-up simulation results with experimental measurements and experimental milling results in laboratory plant EMZ-LAI. With the developed electromagnetic simulations tools an up- and downscaling of EMZ plant is possible.

The energy advantages for dry milling of building materials and wet milling of organic agents are shown using the example of cement clinker and using the example anthraquinone.

The next steps are the connection of developed electromagnetic model with DEM-simulations [8] and a stress model [9] to determinate the required magnet field structure in the air gap for an efficiently milling process.

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Acknowledgment

The authors acknowledge financial support by the German Research Foundation (DFG) (Ha 2338/1) and by the Federal Ministry for Economic Affairs and Energy (BMWi) in ZIM-Cooperation Project EMZ-W (KF2184744KO4) as well as support by several industrial partners.

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