Proposal of Ball Milling System Suitable under the Seafloor for Development of Hydrothermal Deposits by Simulation

Seiji MATSUO1*, Katsunori OKAYA1, Toyohisa FUJITA1, Yasuharu NAKAJIMA2, Sotaro MASANOBU2, Joji YAMAMOTO2 and Ichihiko TAKAHASHI2

1Department of Innovation Systems, School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan
2National Maritime Research Institute, Tokyo 181-0004, Japan

Abstract

Seafloor hydrothermal deposits, which were formed by deposition of precipitates from hydrothermal fluids vented from seafloor, are one of unconventional mineral resources beneath deep seafloors in the Exclusive Economic Zone of Japan. The authors have proposed a concept for Mineral Processing of Seafloor, where useful minerals are separated on deep seafloor and then lifted while remaining gangue is disposed on seafloor in appropriate ways. In this paper the authors studied the new ball milling system which was adapted under seafloor mineral processing. A simulator for ball mill grinding using simple discrete element method was built for this analysis. In this simulation two conditions in ball milling were examined: the method of grinding by enclosing the inside of a ball mill with air and with sea water. Especially we discussed the implementability of the ball mill grinding fulfilled with water because of the ease of installation in the real operation. Consequently, it was suggested that the grinding phenomenon can be performed effectively by the increase in the existence ratio of iron ball in the first quadrant in the mill. In the case where the mill is filled up with the water, it can be expected that crushing efficiency increases by carrying out ball milling at high rotational rate and with the mixture of the small ball size.

Key words: Simulation, Seafloor, Mineral processing, Hydrothermal deposit, Ball mill

1. Introduction

In Japan it is important to search mineral resources, energy resources, and aquatic resource within the territorial waters of Japan and in the exclusive economic zone in the near future, because Japan is surrounded by the ocean and poor in natural resources. The basic plan on ocean energy & mineral resources development was adopted and came into effect in 2009. In this plan, development on the commercial scale of submarine hydrothermal polymetallic ore is recommended and promotion of concrete technical development needs to press. It is thought that the ingredient of submarine hydrothermal polymetallic ore is the same as a black-ore deposit and most of them contain base metal such as copper, a lead and zinc, the precious metals such as gold and silver, a rare metal1. These hydrothermal deposits exist around the world, especially in a mid-ocean ridge and an ocean basin. In the EEZ of Japan, they often lie in Okinawa Trough and the area near from Izu and Ogasawara2. Submarine hydrothermal polymetallic ore in EEZ of Japan exists in a comparatively shallow domain, at a depth of 700–1,600 m, it is suggested that it is comparatively advantageous to development in the world. Ore dressing process is performed ashore in the development of submarine hydrothermal polymetallic ore at present. However, this technique is not economically desirable because all the unprocessed ore is lifted to a mining support vessel, and transported to a mineral processing plant on land. Considering these points, our research team proposed a new concept of mineral processing under the deep ocean floor (Seafloor Mineral Processing) which is intended to develop submarine
hydrothermal polymetallic ore efficiently and economically as shown in Fig. 1. The most significant advantage of adopting Seafloor Mineral Processing is that the amount of the unprocessed ore to the mining support vessel can be reduced. Especially, the grinding system is important in the development of seafloor massive sulfides (Fig. 2).

In this paper, the authors studied the new ball milling system which is adapted to under seafloor mineral processing. A simulator for ball mill grinding using simple discrete element method was built in analysis. The energy dissipation in various conditions, such as the difference in diameter of balls, rotational rate and filling fraction were also examined. Especially we discussed the implementability of the ball mill grinding fulfilled with water because of the ease of installation in the real operation.

2. Ball mill grinding process of the seafloor mineral processing

The Ball mill grinding in seafloor mineral processing is an important system in order to accomplish the floatation of unprocessed ore as shown in Fig. 3. These ores usually need to be crushed to a micron order for the following flotation process. But grinding property in consideration of the high pressure in the bottom of the sea domain and underwater is not researched yet, therefore these researches are urgently necessary towards realization of this process. In order to realize ball milling system under the high water pressure at the bottom of the sea, the following two ball mill operating conditions are assumed: filling up in the ball mill with the gas of about 10 (MPa) and with the seawater (Fig. 4). The former condition possibly causes that the velocity of the ball falls and then the amount of the energy consumption decreases, because the density of the gas increases. The latter condition possibly causes that the velocity of the ball falls considerably because of the influence which is made by buoyancy of the inside seawater and the flow residence. In this analysis, the computer simulation by the simple discrete element method (DEM) was used and verified the differences between these conditions and effective pulverization conditions.

3. The ball mill simulation of the seafloor Mineral Processing

3.1 Simulation conditions

The simulation conditions are given in Table 1,
As can be seen this table, four case studies, i.e., Case A (i), ii) and Case B (iii), iv)), were considered. For instance, the case ii) means that an iron balls is filled with air under the atmospheric pressure. It is assumed that the iron balls in the mill pot is in four conditions, i.e.: 3 cm, 5 cm, 10 cm, 3 cm and 5 cm and 10 cm, respectively. In calculation, the change of the energy dissipation according to mill rotational rate, filling ratio and friction coefficient in balls were investigated.

### 3.2 Discrete Element Method simulation

The discrete element method is simulation technique that models contact forces such as the elastic repulsive force and frictional force working between particles that are in contact with each other and performs a numerical analysis of the motion of the individual particles operated on by the forces of contact based on the equations of motion for each particle. In a ball mill, the collisions between two balls or a ball and the mill wall are expressed by a Voigt model that expresses elastic spring (spring coefficient $K$) where elastic and inelastic properties of the objects are introduced between the points of contact and the viscosity dashpot (damping coefficient $C$) as shown in Fig. 5. The force of contact ($F$) between balls is given by the following equation as the compressive forces in the normal direction:

$$F = -Ku - C\frac{du}{dt}$$  \hspace{1cm} (1)

where, $u$ is the relative displacement between the two particles we are focusing on, and $K$, $C$ are the spring coefficient damping coefficient and coefficient of friction of the balls. Furthermore, the grinding efficiency of the whole ball mill unit was estimated by using energy dissipation in this research. Energy dissipation are described by the following equations (2), (3) by using the viscous coefficient and velocity in the normal direction and tangential direction adjusting to a ball, respectively. This energy is calculated for each contact and summed over all time steps.

$$E_{co} = \sum_{i=1}^{N} \sum_{t} \left(c_n x'_n \times x'_n\right) \Delta t$$  \hspace{1cm} (2)  

$$E_{ft} = \sum_{i=1}^{N} \sum_{t} \left(c_t x'_t \times x'_t\right) \Delta t$$  \hspace{1cm} (3)

where $E_{co}$ is a sum of energy dissipation in horizontal translation, $c_n$ is a coefficient of viscosity in the normal direction, $x'_n$ is a velocity in horizontal translation, $E_{ft}$ is a sum of energy dissipation in the rotational direction, $c_t$ is a coefficient of viscosity in the tangential direction, $x'_t$ is a velocity in the tangential direction, $t$ is simulation time, $N$ is the number of ball.

### 4. Simulation results of ball mill

#### 4.1 The rotational rate

Fig. 6 shows the effect of the energy dissipation on the relative rotational rate against four simulation conditions. Where $N$ is the revolving speed and $N_c$ is the critical revolving speed the ball mill, $J$ is the filling fraction of ball in the mill pot. Considering this figure, when $N/N_c$ is low form 0.7 to 1.0, there was a little difference in the energy dissipation against each case. However, when $N/N_c$ was 1.3, the energy dissipation of the case where the inside of a ball mill is filled in sea water was.

| Table 1 Case studies of computer simulation |
|-------------------------------------------|
| No. | Fluid in ball mill | Pressure [MPa] | Ball Diameter [cm] | Coefficient of friction [-] |
|-----|-------------------|---------------|--------------------|-----------------------------|
| Case A | ii) air | 0.1 | 3.5, 10 | 0.3–1.0 |
| Case A | iii) | | 3–5–10 | |
| Case B | iv) water | 0.1 | 10 | |
| Case B | v) | | | |

| Table 2 Experimental conditions |
|--------------------------------|
| Device | A heading | Unit | Value |
|--------|-----------|------|-------|
| Ball   | diameter  | [cm] | 3, 5, 10, 3–5–10 |
|        | density    | [kg/m$^3$] | 7,870 |
|        | filling fraction [-] | 0.3 |
| Pot    | pot diameter | [mm] | 120 |
|        | pot depth | [mm] | 150 |
|        | critical rotational speed | [rpm] | 122.04 |
|        | pressure | [MPa] | 0.1–10 |
| Ball & Pot | coefficient of friction [-] | 1 |
| Ball & Pot | coefficient of restitution [-] | 0.26 |
| Fluid  | density of air | [Pa s] | 1.293 |
| Fluid  | density of seawater | [Pa s] | 1102.9 |

---

---

---
(case iii), iv)) became low about 20% compared with the energy of the case where the inside is filled with air (case i), ii)).

Figs. 7, 8 show the relation between the rotational rate and the energy dissipation in case of two kinds of ball size; 5 cm only, and 10, 5, 3 cm. As can be seen the figures, the energy dissipation of the case where the ball size is 5 cm became relatively low compared with the energy of the case where the ball size is 10 cm (Fig. 7). In the case where three kinds of balls were mixed, these energy dissipation were larger than that of the case where the ball size is 5 cm again, and the difference of them was about 11~14% when \(N/N_c\) was 0.7–0.9 (Fig. 8).

### 4.2 The filling fraction

Figs. 9, 10 show the sum of energy dissipation as a function of filling fraction in the case of the ball size 10 cm and 5 cm. It was fond that the energy dissipation increased with reduction in a filling fraction when the ball size is 10 cm (Fig. 9). This is considered that an energy loss by friction between iron balls becomes small with reduction.
in a filling fraction. Therefore, the increase in the iron ball speed accompanied by this energy loss affects the increase in the energy dissipation. When a ball 5 cm in diameter is used (Fig. 10), the energy dissipation became relatively low in the same way as Fig. 7. It is considered that when the diameter of a ball is small, even if a filling fraction is small the energy loss by the interaction between balls will not become small.

In addition, Fig. 11 shows the relation between packing ratio and energy dissipation when the three kinds of metal balls is mixed (10 cm, 5 cm and 3 cm). As can be seen this figure, it was found that these energy dissipation were larger than that of the case where the ball size is 5 cm again. The energy dissipation increase when the filling ratio becomes large and it is maximized when the filling ratio \( J \) is 0.3. This filling ratio under seafloor showed the same value as the ratio in the ground.

**4.3 The friction coefficient of iron ball**

Fig. 12 shows the relation between the coefficient of friction and the energy dissipation under the condition which is the rotational speed, \( \frac{N}{N_c} \), is 0.7, filling fraction \( J \) is 0.3. As can be seen this figure, there was little difference in the energy dissipation against each case. The energy dissipation basically tends to increase when a coefficient of friction becomes large.

**5. Proposal of the ball grinding system suitable under the Seafloor**

**5.1 Consideration of the simulation result**

From the previous simulation results, it is found that the energy dissipation of the case where the inside of a ball mill is filled in sea water (Case B) became low about 20% compared with the energy of the case where the inside is filled with air (Case A). This is reason why the fluid in the ball mill rotates at the same speed as the mill. That is, it is thought that the number of the metal ball sticking to the inside wall of the mill increases because of the high fluid density of case B. However, in the case where the small size ball was mixed, these energy dissipations were larger than that of the case where the ball size is 5 cm. It was thought that the grinding efficiency in the seafloor can be sharply increased by mixing many small balls. Furthermore, as shown in Table 3, Case B is considered to be profitable by low cost and the ease of installation compared with Case A in the real operation. Therefore, we discussed the implementability of the ball mill grinding fulfilled with sea water (Case B).

| Table 3 | Comparison of two conditions Case A and Case B |
|---------|------------------------------------------------|
| **The conditions inside mill** | merit | demerit |
| Case A | • low energy loss | • Difficulty of transportation of air to the seafloor |
| Filled air (gas) | | • Progress of corrosion |
| Case B | • low cost | • A grinding energy loss |
| Filled Sew water | • An easy arrangement | | • High Classifier efficiency |

---

Fig. 11  Sum of energy dissipation as a function of filling fraction. (diameter of ball = 10 cm & 5 cm & 3 cm)

Fig. 12  The relation between the coefficient of friction and the energy dissipation.
5.2 Proposal of the optimal ball grinding system when using a mill filled with water

Fig. 13 shows that the relationship between the energy dissipation and the rotational rate, when the diameter of the metal ball is 3 cm. As can be seen this figure, it was found that the energy dissipation of the case B become considerably large on condition of the smaller diameter of a ball. Fig. 14 shows one situation of the simulation of the ball mill grinding under the two cases, Case A and Case B. In Case A, the ball falls to the 4th quadrant domain of the two-dimensional space shown in this figure since the influence of the ball on fluid is small. On the other hand, in Case B, it turns out that the ball has fallen to the 3rd quadrant domain because the ball is greatly influenced by the fluid flow. For this reason, since the collision ratio

![Graph showing the relationship between rotational rate and energy dissipation](image)

**Fig. 13** The relation between the rotational rate and the energy dissipation. (diameter of ball = 3 cm)

![Diagrams of ball milling](image)

(a) Air – under 0.1 MPa (Case A)  
(b) Sea water – under 10MPa (Case B)

**Fig. 14** The animation of ball milling obtained from the simulation in two conditions.

![Diagrams of ball milling](image)

\[
\frac{N}{N_c} = 0.7 \quad \text{Ball dia.} = 10\text{cm}, \quad J = 0.3, \text{Simulation time} = 20\text{s}
\]

**Fig. 15** Comparison of distribution state of iron ball in the first quadrant domain in case B.
between the balls in Case B increases remarkably compared with that of Case A, it is suggested that energy dissipation increased. Therefore, it was thought that the grinding efficiency in the seafloor can be sharply increased by mixing many small balls.

Fig. 15 shows the animation of ball milling obtained from the simulation in case of two conditions: low rotational rate and high rotational rate in Case B. As shown in this figure, when the revolution rate $N/N_c$ is high (1.3), the existence ratio of iron ball in the first quadrant is larger than the case of low rotational rate ($N/N_c = 0.7$). Fig. 16 shows the existence rate of iron ball in the first quadrant domain of the two-dimensional space under two cases, (Case A, Case B). This graph shows that the existence ratio of iron ball in the first quadrant domain increased when the relative rotational rate $N/N_c$ is high. The existence rate in the first quadrant domain in the case that the inside of mill is filled with water (Case B) became large compare with that in the case where the inside of mill is filled with air (Case A). When the inside of the ball mill pot is filled with air, the iron ball located in the bottom of the mill pot and the crushing phenomenon occurs only in this area. But it is thought that when the inside of the ball mill pot is filled with sew water, the iron ball is located in some places and grinding phenomena increase by this effect.

From these considerations, it is suggested that the grinding phenomenon can be performed effectively because the existence ratio of iron ball in the first quadrant rate become large. In the case where the mill is filled up with the water, it can be expected that crushing efficiency increases by carrying out ball milling at high rotational rate and with the mixture of the small ball size.

6. Conclusions

The authors studied the new ball milling system suitable under seafloor mineral processing which is more important for development of seafloor massive sulfides. A simulator for ball mill grinding using simple discrete element method was built for this analysis. In this simulation two conditions in ball milling were examined: the method of grinding by enclosing the inside of a ball mill with air and sea water. The energy dissipation in various conditions, such as the difference in diameter of balls, rotational rate and filling fraction were also examined. Especially, we discussed the implementability of the ball mill grinding fulfilled with water. Because of the ease of installation compared with the case of air in the real operation.

Consequently, it was suggested that the grinding phenomenon can be performed effectively because the existence ratio of iron ball in the first quadrant rate become large. In the case where the mill is filled up with the water, it can be expected that crushing efficiency increases by carrying out ball milling at high rotational rate and with the mixture of the small ball size.

Acknowledgments

This study was financially supported by Grant-in-Aid for Scientific Research (B), No. 22360373, for the Promotion of Science (JSPS). The authors express our deep appreciation to all parties concerned.

References

1. P.A. Rona and S.D. Scott: Economic Geology, 88, pp. 1935–1976 (1993)
2. G.P. Glasby, K. Iizasa, M. Hannington, H. Kubota, K. Notsu: Ore Geology Reviews, 34, pp. 547–560 (2008)
3. Y. Nakajima, S. Uto, S. Kanada et al.: Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering, (Rotterdam), pp. 1–6 (2011)
4. C. Tokoro, T. Yamashita et al.: Resources Processing, 56, pp. 113–119 (2009)
5. H. Ryu, H. Hashimoto, F. Saito, R. Watanabe: Shigen-to-Sozai, 108, pp. 549–555 (1992)
6. R.K. Rajamani, B.K. Mishra, R. Venugopal, A. Datta: Powder Technology, 109, pp. 105–112 (2000)
7. Y. Inoue, T. Yokoyama, T. Tanaka, Y. Tsuji: The Japan Society of Mechanical Engineers, 66, pp. 1–8 (2000)