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Original Research Paper

Analysis of dynamic similarity and energy-saving mechanism of the grinding process in a horizontal planetary ball mill

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ABSTRACT

In this paper, we discretized the ball motion in a horizontal planetary ball mill, the fundamental equation of the relative motion and the detaching trajectory were analyzed, and the impact time was approximately formulated. We performed experiments on impact comminution and observed that an equal impact potential energy causes an equal grinding effect. Based on theoretical analysis, comparing the horizontal planetary ball mill whose planetary factor is z with the traditional ball mill through dynamic similarity principles, the results show that when dynamic similarity exists and when the grinding outputs of each mill are equal to each other, the radius of horizontal planetary ball mill is $z^{-1/4}$ times as the radius of a traditional ball mill. If the impact potential energies of the balls in these two mills are the same, the impact stress of the balls in a horizontal planetary ball mill is z times as in a dynamic similarity traditional ball mill. To determine the equal grinding effect, the energy consumption of a horizontal planetary ball mill is $z^{-3/8}$ times as that of traditional ball mill.

1. Introduction

Two different types of planetary ball mill exist. One is by vertically placing its vials, which is common, and the other is by placing vials horizontally, as showed in Fig. 1.

The planetary ball mill has a similar grinding principle to a traditional ball mill. However, compared with a traditional ball mill, the vials of a planetary ball mill are capable of both rotation and revolution. As such, the planetary ball mill has been widely used in various areas such as in the preparation of ultrafine powder, mechanochemical process, and mechanical alloying because of its high grinding ability and energy utilization ratio [1,2]. Feng [3], Mio [4–6], and Sato et al. [7] performed computational simulation by using the discrete element method (DEM) to analyze the influence of the grinding media on the impact force, which was caused by changing the structural parameters of the vertical planetary ball mill. They concluded that when the rotation and revolution had different directions, the impact energy and frequency of the balls were far greater than the ones when the directions were the same. The impact energy of the balls directly increased with the revolution speed and the rotation to revolution speed ratio but decreased at a critical speed ratio (which is an important operating parameter). Moreover, they established the equation of amplification factor t_p and the total impact energy of balls $E_i \infty t_p^{4.87}$. Chattopadhyay et al. [8] carefully studied the motions and mechanics of the balls in a planetary ball mill, and the results indicated that the revolution speed exerted the most significant influence on the radial force. The direction of tangential force determined the effectiveness of the impact. Moreover, the total power was computed as a function of the revolutionary speed. Lu et al. [9] employed a kinetic model to simulate the trajectory of a single ball in a planetary ball mill and proposed a model to explain the energy transfer during the milling process. Yazdani et al. [10] developed a System Dynamics (SD) model to study how the geometry size and operating parameters affect the impact energy, milling temperature, and decrease in particle size during the milling process.

During 1990s, Yan [11–14] was the first to carry out the research on horizontal planetary ball mill, where he analyzed the optimal operating parameters, mechanism of ultrafine powder preparation, and impact energy. Similarities were observed between the vertical and horizontal ball mill during the grinding process. For instance, the calculating methods of the critical rotation speed are nearly the same. However, other researchers found that differences exist between the two types of ball mill. Cai et al. [15,16] obtained the optimal parameters of the horizontal

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planetary ball mill for grinding the cement clinker, and they further studied the influence of the lining plate in the vial. The result shows that the optimum thickness is 3 mm. At this thickness and at a centrifugal acceleration of 14*g* and a grinding time of 5 min, a production rate of 66.62% can be obtained, which is the best grinding efficiency. Zhu et al. [17,18] performed numerical simulations of the horizontal planetary ball mill by using DEM to study the ball motion in the vial and the optimal operating parameters for the mill. The results indicated that the grinding rate could be determined using the mean contact force and that the logarithm of grinding rate was a linear function of the mean contact force, whose slope was 0.087.

Previous studies have elaborated on the grinding mechanism of the planetary ball mill and the kinetics and dynamics of the balls and ground materials during the grinding process. However, compared with the traditional ball mill, the extent of improvement in energy utilization and the grinding ability when the planetary ball mill is used should be determined. In 2008, Yan et al. [19] discussed this issue based on the material fatigue damage accumulation theory, which shows that the energy-saving mechanism was affected by both the working condition of the mill and the grinding-related physical properties of the powder. Furthermore, mathematical and statistical concepts and the Hertz stress calculation method were applied to formulate the stress distribution of the powder, the effect of fatigue damage accumulation, and model of the relationship of planetary and energy-saving effects. Finally, depletion efficiency of the powder effect was proposed to interpret quantitatively the energy-saving mechanism of the planetary ball mill. However, Yan's work is purely hypothetical. As such, it lacks verification of adequate accepted theory and experimental data. Thus, further studies are carried on in this paper. Dynamic similarity principles were employed to analyze the horizontal planetary ball mill and the traditional ball mill. And combined with essential experiment, the energy-saving mechanism was analyzed too.

2. Theoretical approaches and discussions

2.1. Ball motion in a horizontal planetary ball mill

The impact and grinding process in a horizontal planetary ball mill could be essentially explained by impact dynamics. The process conforms to dynamic similarity principles, which include geometry, kinematic, and dynamic similarities.

According to the previous research [4,6,8,10], when discussing the dynamics of planetary ball mill, the main impact and grinding effect was due to the centrifugal force, the gravity effect was relatively small, and so was the frictions of the ball. So, the influence of gravity and frictions of the ball were neglected in this model.

2.1.1. Fundamental equation of the ball's relative motion

The ball motion in a single vial of horizontal planetary ball mill could be characterized as a relative motion in an inertial coordinate system whose convected acceleration is revolution centrifugal acceleration located at the center point of the vial. The forcing system of a typical ball in this coordinate system is shown in Fig. 2 (the influence of gravity is neglected).

When the vial rotates, the balls inside make a relative circular motion, which could be formulated as follows:

$$N + G\cos\varphi = mr(\Omega - \omega)^2 \tag{1}$$

and

$$G = mR\Omega^2 = mzg \tag{2}$$

where N is the reaction force of the vial wall against the ball, G is the centrifugal force of revolution, m the mass of the ball, r is the radius of rotation (e.g., the distance between the center of the ball and the center of the vial), Ω is the angular speed of revolution, ω is the relative angular speed of vial rotation, R is the radius of revolution of the vial's center point, z is the planetary effect, and g is the acceleration of gravity.

The planetary factor z mentioned above is a parameter that can be used to represent the efficiency of the planetary ball mill and is expressed as:

$$z = \frac{a_i}{g} = \frac{R\Omega^2}{g} \tag{3}$$

When the ball begins to detach, $F = 0$ and $N = 0$. As such, based on Eqs. (1) and (2):

$$\cos\varphi = \frac{r(\Omega - \omega)^2}{R\Omega^2} = \frac{r(\Omega - \omega)^2}{zg} \tag{4}$$

which is the fundamental equation of the ball's relative motion in the vial. From Eq. (4), the detach angle is related to the effective radius of the vial, the relative angular speed of vial rotation, the radius of revolution, and the angular speed of revolution, but it is not related with the mass of the grinding ball itself.

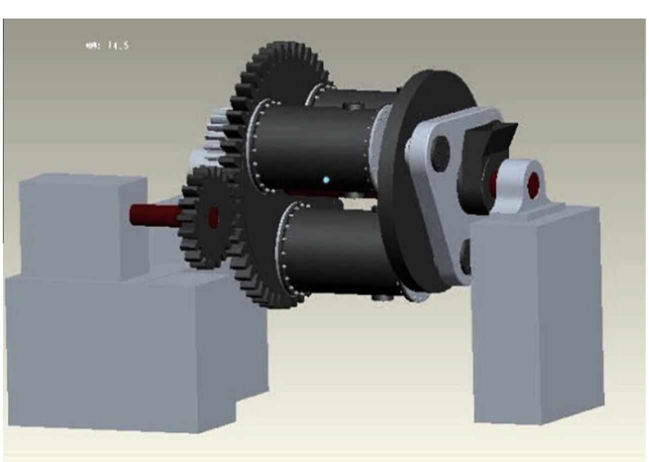

Fig. 1. Horizontal planetary ball mill.

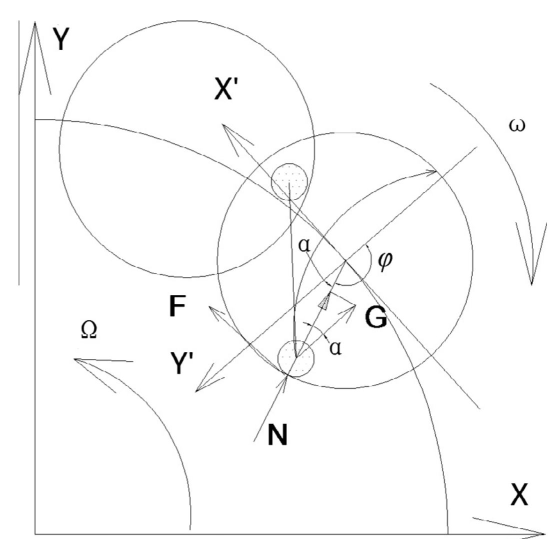

Fig. 2. Force diagram of a ball in an inertial coordinate system.