

Research Article

New Challenge on Determination of the Reasonable Rotation to Revolution Speed Ratio for the Mechanical Activation of Boron Concentrate in Planetary Ball Mill

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Abstract

The planetary ball mill is extensively used for grinding, mechanical activation, mechanical alloying, and mechanochemical synthesis of different substances including nanomaterials. It is very important to determine the optimal operating parameters for high efficiency of the planetary ball mill. However, it is difficult to determine the optimal operating conditions for the planetary ball mill because the motion mechanism within the vial is too complex and many factors affect the motion and they are closely related to each other. In particular, the type and property of powder materials have a great influence on the ball motion and energy, and the optimum operating parameter values, even the ball motion state or mechanism, are different from each other in many studies. In this paper, the effect of the rotation to revolution speed ratio on the several interaction forces, such as the normal, tangential, compressive, and total forces, in the planetary ball mill using discrete element method is investigated for determination of the reasonable rotation to revolution speed ratio for the mechanical activation of boron concentrate. The normal and total forces have maximal values at RRSR = 4-4.5, however, the tangential and compressive forces have no maximal value and continue to increase. The action of the normal force might be greater than both of the tangential and compressive forces, moreover, there might be the action of the total force. It is difficult to determine the optimal rotation-to-revolution speed ratio by consideration with only a few factors such as normal, tangential, compressive and total forces in planetary ball mill, therefore, further research is needed.

Keywords

Speed Ratio, Contact Force, Compressive Force, Mechanical Activation, Planetary Ball Mill

1. Introduction

In recent years, there has been an increasing interest in the application of mechanical activation to enhance hydrometallurgical processes, which have been used for the pretreatment of various minerals and can be further used as an effective method to enhance the reactivity of various

materials [1]. The planetary ball mill is extensively used for grinding, mechanical activation, mechanical alloying, and mechanochemical synthesis of different substances including nanomaterials [2-5].

The planetary ball mill consists of a supporting disk and

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two or more milling vials, providing high energy due to the overlapping effect of two centrifugal fields caused by the revolution of the disk and the counter rotation of the vial around its own axis [6]. When the planetary ball mill operates at high speed, the movement of the balls and powder particles in the vials is very complex and irregular, and it produces various mechanical forces between the balls, the powder particles, and the vial wall, such as collision, shear, and compressive forces [7]. The change of the operating parameters during mechanical activation have a direct effect on the magnitude and direction of such mechanical forces, thereby controlling the grinding efficiency of powder and their crystal structure change.

In the recent years, the many researches have been carried out to model the motion of between the ball and the powder particles and their mechanical action with operating parameters in planetary ball mill, and the most studies have considered the collision between the ball and the particle as the primary parameter [8-11]. However, in-situ observations have not shown that the grinding effect is solely due to the collision, and the actual situation is much more complicated due to various types of interactions between ball-ball, ball-particle, and particle-vial [12-14].

Many researchers have studied the effects of the ball to powder ratio (BPR), the size and type of ball, the filling ratio, the rotation speed, and the rotation to revolution speed ratio (RRSR) on the grinding efficiency and the powder properties for the planetary ball mill by the simulation using DEM software [15-18]. However, it is difficult to determine the optimal operating conditions for the planetary ball mill because the motion mechanism within the vial is too complex and many factors affect the motion and they are closely related to each other. In particular, the type and property of powder materials have a great influence on the ball motion and energy, and the optimum operating parameter values, even the ball motion state or mechanism, are different from each other in many studies. Some studies [19] reported that the favorable movement of the ball for grinding was “cascading” regime and the reasonable RRSR value was 3.6-4, but other researchers [14] reported that the “cascading” regime was advantageous for grinding and the reasonable RRSR was 1.5. In many studies [11, 13-15, 20-23], the reasonable RRSR values were between 1.3 and 3.1.

Although there have been many studies [6, 15, 17, 19, 24] that considered collisions between balls and powder particles as the primary factor, some researchers [12, 14, 25, 26] concluded that the attrition and the wear was more important factors for the planetary ball milling process.

These results indicate that the milling process in the planetary ball mill is very intricate and the optimal parameters depend on many factors such as the operating condition, the properties of powder materials, and so on.

Boron is a significant element for not only the industrial production but also in defense construction, nuclear industry,

and science and technology [27], so some researchers [25] have investigated the effect of different parameters, such as ball to powder ratio, ball diameter, filling ratio, and revolution speed (in the case of RRSR=2), on the surface area of the powder in the mechanical activation process of boron concentration by the planetary ball mill. They reported that the contact forces (the normal force and the tangential force) and compressive force was very significant and the greater the compressive and contact forces, the greater the surface area. However, it is unsatisfied that they did not consider the effect of RRSR on the mechanical activation in the planetary ball mill.

The purpose of this paper is to provide the reasonable RRSR value for the mechanical activation of the boron concentrate in the planetary ball mill. We have considered the effect of RRSR on the several interaction forces, such as the normal, tangential, compressive, and total forces, in the planetary ball mill using discrete element method.

2. Method and Simulation

2.1. Discrete Element Method

The simulations were carried out using EDEM 2024, the high-performance discrete element method (DEM) simulation software. EDEM provides many methods for theory and simulation regarding the contact model, the most used models are Hertz-Mindlin (no-slip), Hertz-Mindlin (no-slip) with RVD Rolling friction, Hertz-Mindlin (no-slip) with JKR Cohesion, and so on [28]. Hertz-Mindlin (no-slip) contact model is the default model used in EDEM due to its accurate and efficient calculation for the forces. The normal force and the tangential force model in this model are based on Hertzian contact theory and Mindlin Deresiewicz model, respectively. Both normal force and tangential force have damping components where the damping coefficient depends on the restitution coefficient. The tangential friction force is based to the Coulomb law of friction model. The rolling friction uses the independent directional constant torque model for the contacts [29]. In this paper, the default model of EDEM, Hertz-Mindlin (no-slip) contact model, is used.

2.2. Instrument

In the simulation, Pulverisette 4 high-energy planetary ball mill (produced by the German Fritsch Company) was used. Figure 1 shows the operating principle of the planetary ball mill. The operating parameters for simulation are taken by the earlier work, that is, the ball to powder ratio (BPR) is 12, the ball size is 8mm, the filling ratio is 50%. The planetary ball mill, zirconia vials (250mL), and zirconia balls (8mm) used in the simulation are shown in Figure 2. The interior dimension of the vial is shown in Figure 3, respectively [25].

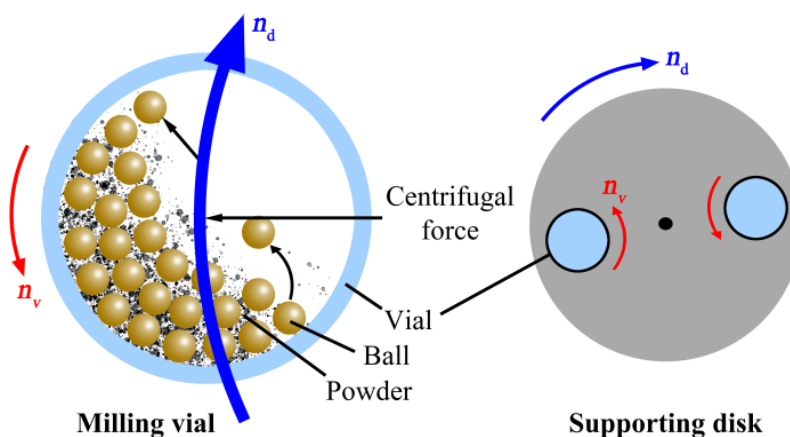


Figure 1. The operating principle of the planetary ball mill.



Figure 2. Planetary ball mill, zirconia vials, and zirconia balls.

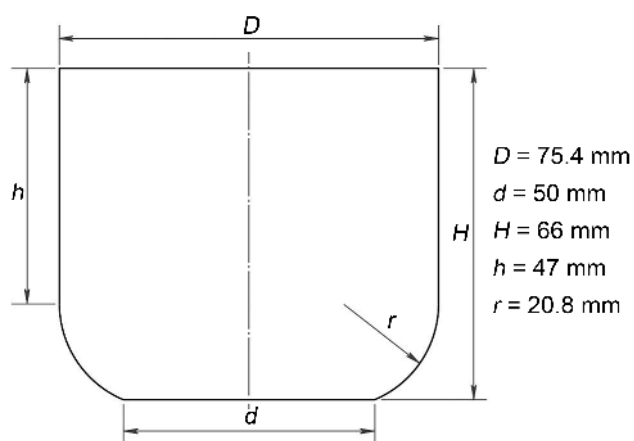


Figure 3. The geometrical dimensions of the milling vial.

2.3. Simulation

The parameters, were selected from the measurements and references [25], are shown in Table 1. The simulation was

carried out by changing the revolution speed and the rotation speed at the range of from 1 to 5 of RRSR. In order to reduce calculation cost, it is assumed that the powder particle was single sphere with 1.2mm of diameter [26]. The movement pattern for balls and particles in the vial, the normal force,

the tangential force, compressive force, and total force were considered with the change of RRSR. The simulation method

seems that there is no need to be validated., because it had already been verified in the preceding work [25].

Table 1. The parameters for EDEM simulation [25].

Parameter	Value	Unit
Revolution speed N_d	100-500	rpm
Rotational speed N_v	100-2500	rpm
Revolution radius R_d	125	mm
Vial radius r_v	37.7	mm
Density of ball and vial ρ_b	5700	kg/m ³
Density of powder ρ_p	1300	kg/m ³
Poisson's ratio of ball and vial ν_b	0.27	-
Poisson's ratio of powder ν_p	0.3	-
Young's modulus of ball and vial E_b	2.1×10^{11}	Pa
Young's modulus of powder E_p	1×10^7	Pa
Restitution coefficient of ball-ball and ball-vial	0.8	-
Static friction coefficient of ball-ball and ball-vial	0.5	-
Rolling friction coefficient of ball-ball and ball-vial	0.01	-
Restitution coefficient of powder-powder	0.3	-
Static friction coefficient of powder-powder	0.7	-
Rolling friction coefficient of powder-powder	0.15	-
Restitution coefficient of powder-ball and powder-vial	0.5	-
Static friction coefficient of powder-ball and powder-vial	0.7	-
Rolling friction coefficient of powder-ball and powder-vial	0.15	-
Time step is set 20% of the Rayleigh time step		

3. Results and Discussion

3.1. The Movement Regime with RRSR

The effects of RRSR on the ball motion pattern in the planetary ball mill was considered as shown Figure 4. As shown in the figure, there are all three motion regimes of "cascading", "cataracting", and "centrifuging" within the given ranges of revolution speeds and RRSRs, which the

RRSR for the transition are different each other with the revolution speed. For example, in the case of 200 rpm of the revolution speed, it is switches from "cascading" to "cataracting" at RRSR=3.5-4 and to "centrifuging" at RRSR=4-4.5, but in the case of 300rpm, changes to "cataracting" at RRSR=4 and to "centrifuging" at RRSR=4.5. In all the cases, the RRSR values for the transition from "cascading" to "cataracting" is not clear, which seems to be related to the high charging ratio.

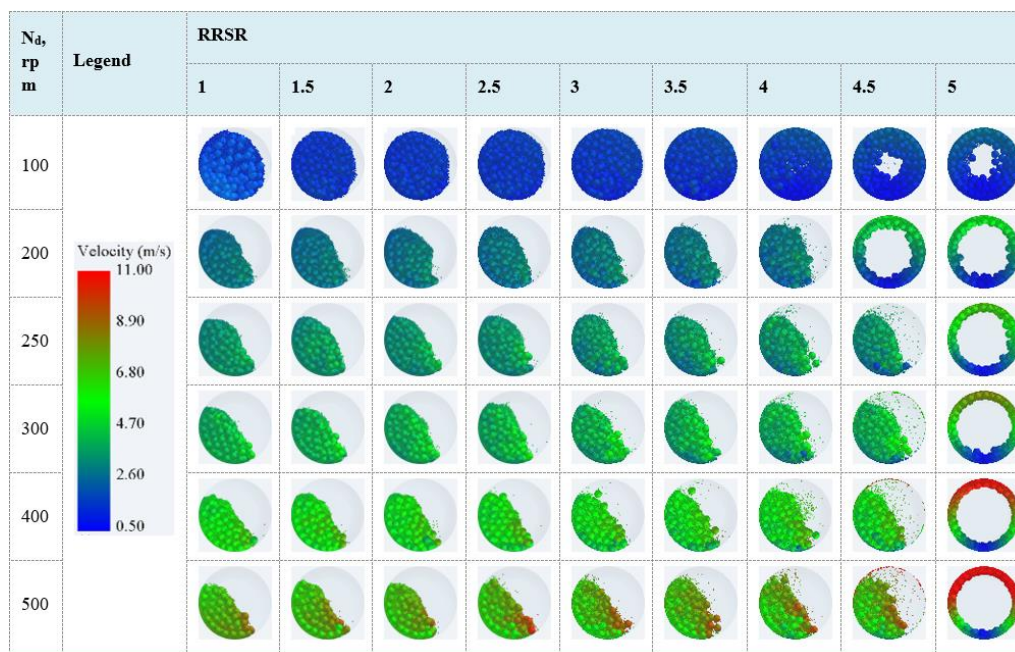


Figure 4. The movement regime with RRSR.

3.2. The Change of the Forces with RRSR

In some studies [12, 13, 25, 26] reported that the planetary ball milling process should be described in terms of wear and attrition and not impact, some researchers claimed that the grinding efficiency has a closed relationship with the normal/tangential/compressive forces [25]. We have considered the effects of RRSR on the normal, tangential, compressive, and total forces. The normal force is the forces that arises when two bodies are in direct contact with one another, which always acts perpendicular to the body that applies the force. The tangential force is the forces from the tangential overlap. The compressive force (see Figure 5) is the sum of the surface normal force magnitudes. The total force is the resultant unbalanced forces on a particle or geometry element in x, y, and z.

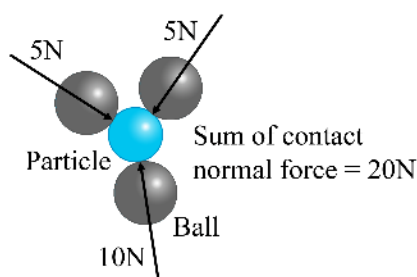


Figure 5. The concept of compressive force.

RRSR is constant, the magnitude of the normal force gradually increases with increasing the revolution speed, and when the revolution speed is not change, the normal force gradually increases and rapidly decreases with increasing RRSR. In the same of revolution speed, the peak position of the maximal magnitude of the normal force is slightly different with the revolution speed. There is no peak for 100rpm and it appears at RRSR=4 for 200rpm and 500rpm, while it appears at RRSR=4.5 for 250rpm, 300rpm, and 400rpm. That is, the maximal value of the normal force is at RRSR=4.5.

In the case of more than 300 rpm of the revolution speed, the magnitude of the normal forces does not continuously increase, the increase and decrease are alternated with RRSR. This tendency appears in the case of tangential force (see Figure 8 and Figure 9), too.

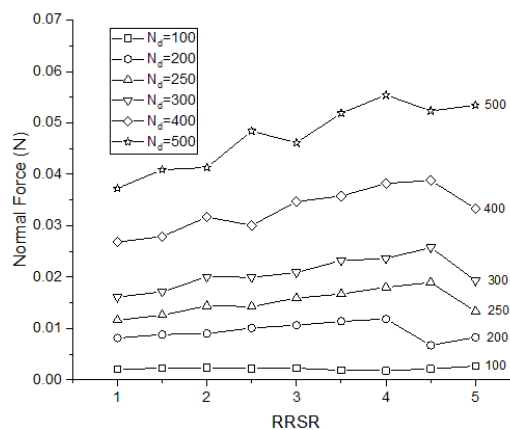


Figure 6. The normal force with RRSR.

Figure 6 and Figure 7 show the normal forces with RRSR and the revolution speed. As shown in the figures, when

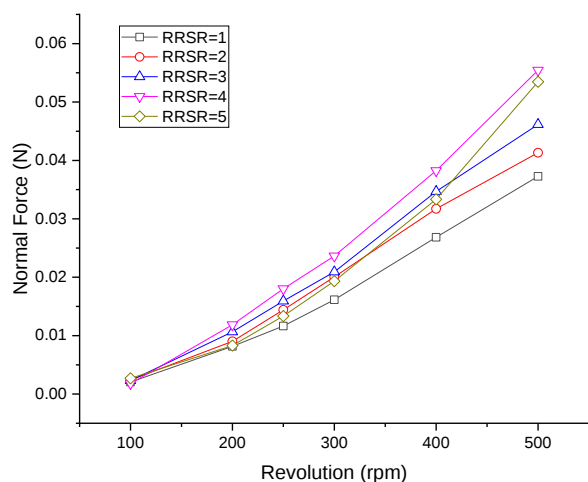


Figure 7. The normal force with the revolution speed.

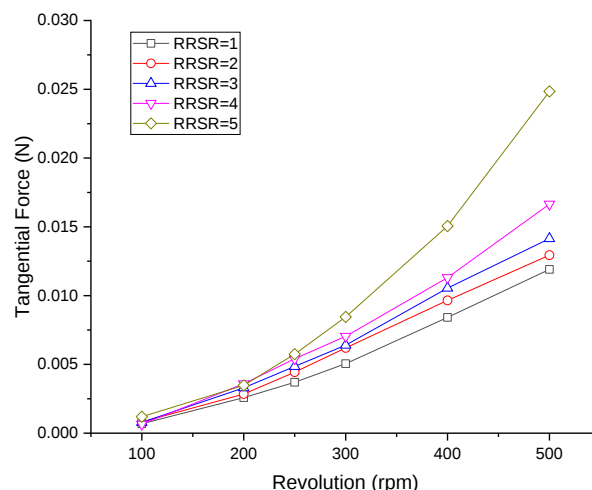


Figure 9. The tangential force with the revolution speed.

Figure 8 and Figure 9 show the tangential forces with RRSR and the revolution speed. As shown in the figures, when RRSR is constant, the magnitude of the tangential force also gradually increases with increasing the revolution speed, and when the revolution speed is not change, the tangential force gradually increases with increasing RRSR and rapidly increases from RRSR=4.5 at the high revolution speed (see 400rpm and 500rpm of revolution speed in Figure 8). There is no a peak for tangential force at all the case, the greater both RRSR and the revolution speed, the greater the tangential force.

Figure 10 and Figure 11 show the compressive forces with RRSR and the revolution speed. The figures indicate that when RRSR is constant, the magnitude of the compressive force gradually increases with increasing the revolution speed, while at the same revolution speed, it remains almost constant with increasing the RRSR, however, rapidly increases from RRSR=4.5. But when the revolution speed is 500rpm, the magnitude fluctuation of the compressive force is not small. That is, the compressive force also has no peak, is almost constant, rapidly increase from RRSR=4.5.

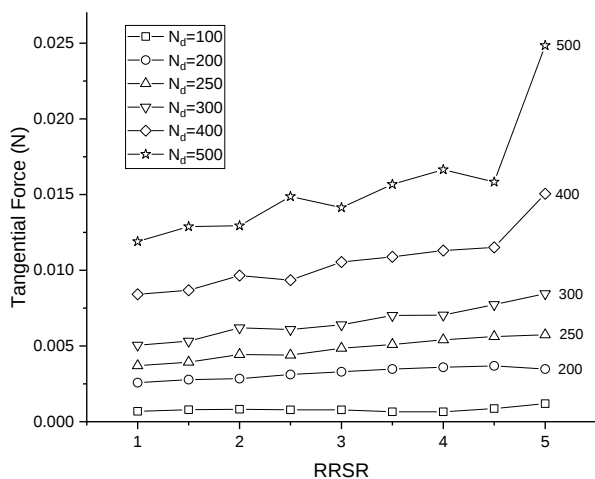


Figure 8. The tangential force with RRSR.

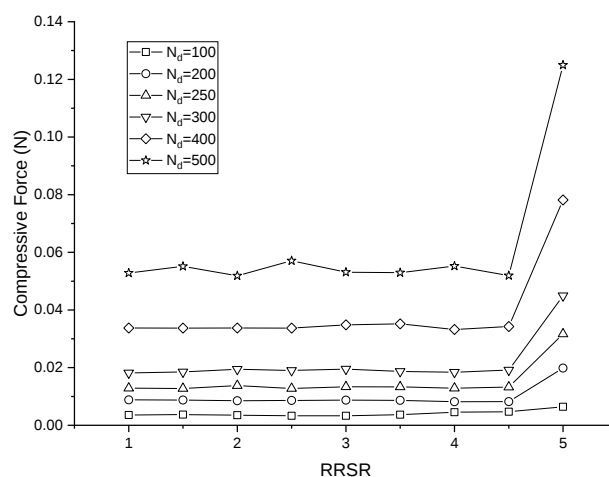


Figure 10. The compressive force with RRSR.

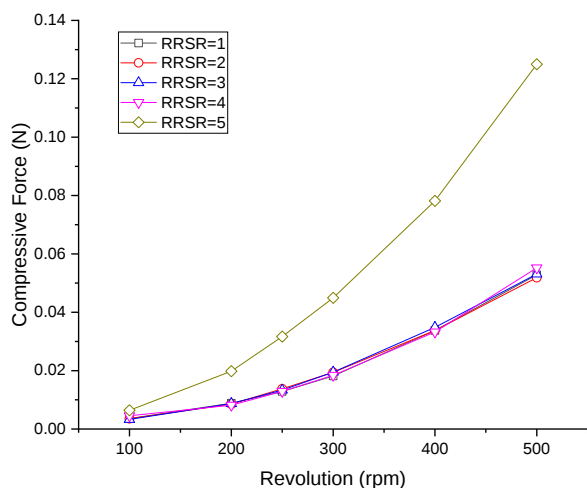


Figure 11. The compressive force with the revolution speed.

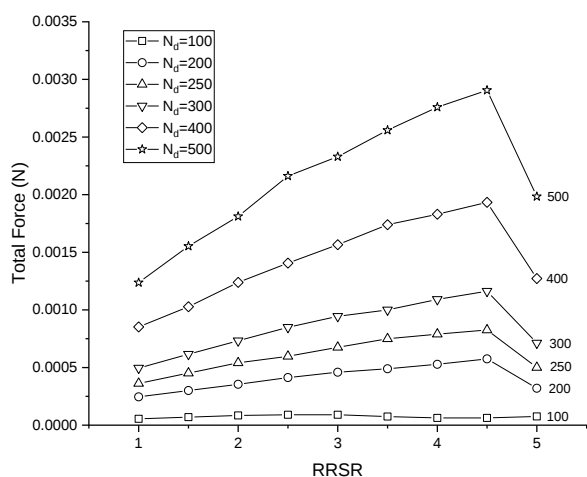


Figure 12. The total force with RRSR.

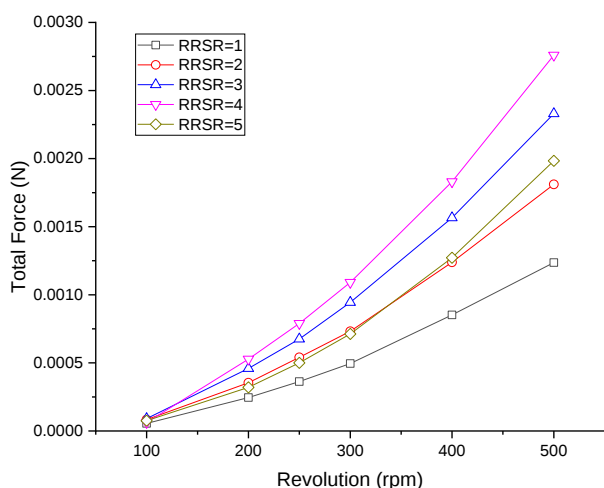


Figure 13. The total force with the revolution speed.

Figure 12 and Figure 13 show the total force with RRSR and the revolution speed. As shown in the figures, when RRSR is constant, the magnitude of the total force constantly

increases with the revolution speed, and when the revolution speed is constant, the total force gradually increases with RRSR and rapidly decreases from RRSR=4.5 at more than 200rpm of the revolution speed. In other words, when the revolution speed is more than 200rpm, the compressive force has a maximum at RRSR=4.5.

There is no clear boundary in which the motion regime is transferred from "cascading" to "cataracting" in from Figure 6 to Figure 13, which will be related to the high filling ratio of ball and powder, as mentioned above. The simulation results show that the normal and total forces have maximal values at RRSR=4-4.5 and the tangential and compressive forces have no maximal value and increase constantly. As mentioned above, the higher the normal, tangential, and compressive forces, the greater the grinding effect. However, the results indicate that the action of the normal force might be greater than both of the tangential and compressive forces, and that the contribution of the total force might also be large. RRSR=4-4.5, where the normal and total forces have maximal values, is the last "cataracting" movement regime before the transition to "centrifuging" regime, and it is difficult to say that this is the optimal RRSR value because the tangential and compressive forces continue to increase. This result shows that the optimal RRSR value depends on a lot of factors and that it is impossible to determine this value with only a few factors.

4. Conclusion

In this work, we have investigated the effect of RRSR on the normal, tangential, compressive, and total forces in the planetary ball milling process with computer DEM simulation. The conclusions are as follows.

- 1) The normal and total forces have maximal values at RRSR=4-4.5, however, the tangential and compressive forces have no maximal value and continue to increase.
- 2) The action of the normal force might be greater than both of the tangential and compressive forces, moreover, there might be the action of the total force.
- 3) It is difficult to determine the optimal rotation-to-revolution speed ratio by consideration with only a few factors such as normal, tangential, compressive and total forces in planetary ball mill, therefore, further research is needed.

Abbreviations

BPR	Ball to Powder Ratio
RRSR	Rotation to Revolution Speed Ratio
DEM	Discrete Element Method

Acknowledgments

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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