Discrete element method simulations of load behavior with mono-sized iron ore particles in a ball mill

Yuxing Peng¹,², Tongqing Li¹,², Zhencai Zhu¹,², Shengyong Zou³ and Zixin Yin¹,²

Abstract
Aiming at addressing the load behavior of iron ore particles in a ball mill, a design of experimental method was used to define a series of discrete element method simulation conditions with two factors being the mill speed and lifter height. The key feature locations of impact toe, bulk toe, shoulder, and head positions were identified visually to determine the load behavior of the charge. To allow the irregular particle shape to be accurately determined, a quick and accurate sphere-clump method was employed in modeling the geometrical model of irregular shape. The results show that the dependence of the impact toe and head on mill speed is higher than its dependence on the lifter height with a correlation of 0.923 and 0.97, respectively. The shoulder changes approximately invariant with the mill speed and varies little with the lifter height. The bulk toe of particles appears to be invariant to the mill speed as well as the lifter height, resulting in the approximately same inclination of the chord joining the shoulder and bulk toe.

Keywords
Load behavior, iron ore particles, sphere-clump method, discrete element method simulation, ball mill

Date received: 15 November 2016; accepted: 27 March 2017

Academic Editor: Filippo Berto

Introduction
Iron ore is the primary source for iron- and steel-making industries, which use the tumbling mills for further comminuting to get the required particle size distribution. Establishing power equation of tumbling mill has been investigated intensively for many years. Many researchers assumed that the en-masse mass was located below the line joining the toe and shoulder and the power equation was established on the basis of torque-arm principle.¹,² The method provided a concise assumption that incorporated all active charge into a point. The size between mill center and this point was the key feature to determine the mill power, while this size was intimately related to the load behavior of the charge.³ Currently, the key location features (impact toe, bulk toe, shoulder, and head position) were extensively adopted to represent the charge behavior, which provided an elegant description to determine the load behavior quantitatively.⁴,⁵

Generally, the charge inside the mills moves upward and reaches a force balance point (shoulder position). Subsequently, the charge flows downward with a typical trajectory from the shoulder, coming into contact with the liner as a cascading or cataracting style...
(toe position). Along this trajectory, the highest point of
the liner that is in contact with the charge is called head
position. Currently, with the application of large or steep
lifters, the charge will throw higher and impact on the
liner in a region above the toe position. The top of this
direct liner impact region is usually called impact toe. In
the toe region, the highest point reached by the bulk of
the charge is usually called the bulk toe. To sum up, the
positions of the four key features of the charge provide
profound information about the current operation of the
mill and can be employed in optimizing the mill.

It is well known that the lifter profiles hitherto
extensively used in the semi-autogenous grinding
(SAG)/autogenous grinding (AG) or the primary mills
are lifter bars and trapezoid lifters. Lifter plays a vital
role in protecting the mill shell from wear due to its
strong influence on the load behavior of charge beha-
vor as well as the grinding efficiency. A portion of ca-
ataracting is used for increasing the impact energy for
particle breakage, while a portion of cascading is used
for the abrasion and attrition. Morrell presented that
the mill power was only dependent on the active
charge, and the charge in the cataracting region had no
impact on the mill power. And then a simplified charge
shape, namely, crescent-like shape, was presented in his
theoretical model of mill power draw. According to the
theoretical model, the positions of toe and shoulder
were strong dependence on mill fillings and speeds,
while the positions of toe and shoulder appeared to be
invariant to the liner shape. However, Powell and
Nurick have put forward that the power draw was not
invariant to the liner shape. Currently, Powell’s model has been tested
by many scholars on the basis of PEPT (positron emis-
sion particle tracking). Hence, the power draw cal-
culated by Morrell’s theoretical model is small.
Currently, advances in computing speed and power as
well as improvements in programming (such as particle
tracking technology), the determinations of COC (cen-
ter of circulation), and COM (center of mass of charge)
have become the key parameters to study the power
draw of mill. Therefore, the mill load behavior
highly depends on the liner shape and should be stud-
ied accurately. As the lifter wears, the reduction in its
dimensions definitely results in the variation of the
impact toe, bulk toe, and the position of shoulder and
head. Besides, many researchers demonstrated that
the key location features are highly sensitive to critical
mill parameters such as mill speed and filling.
Therefore, it is of economic importance to address the
influence of operating parameters and lifter profile on
the load behavior. In China, the largest ball mill of
7.9 m in diameter and 13.6 m in length was developed
and applied successfully in a mine. It is also intensively
recognized that the wave lifter profile is widely used for
the ball mill. However, little study has been addressed
on the wave lifters.

In the last few decades, the discrete element method
(DEM) has been successfully applied for describing the
motion properties of particles, with many industrial
applications ranging from chemical to metallurgy indus-
tries. In order to apply the powerful numerical
method qualitatively, it is now intensively recognized
that it is highly desirable for predicting what happened
in reality as well as the quantitative accurate informa-
tion representation. The exact definition of real particle
shapes hitherto is one of the key issues to be solved.
Many investigators employed the simple spherical shape
in the majority of DEM simulations to achieve a reason-
able simulation time, whereas it is apparent that the
shortcomings of unrealistic simplifications and assump-
tions are also clear. These simplified models are an
unrealistic measure on both the physical properties and
contact parameters, as well as poor particle representa-
tion on packing characteristics. In ball milling, the geo-
metrical shapes of iron ore particles are highly irregular
because of the breakage behavior. Therefore, modeling
the contact model with irregular shape is essential and
worthwhile for DEM simulations. Along with the fast
development of X-ray and image processing technique,
the multi-element spheres method has been used success-
fully to represent the geometrical model of irregular iron
ore particles. To achieve an accurate representation
of particle shape, a large number of spheres are used for
describing information about the details. Due to com-
puting considerations, there are some limitations in the
current state of the art for DEM software especially for
industrial application. In particular there are restrictions
on shape of particles that can realistically be modeled.
Therefore, considering the accuracy in describing the
shape of iron ore particles and computational effort, the
appropriate geometrical shape of irregular particles
should be carefully modeled.

This article aims to study the influences of mill speed
and wave lifter profile (wear state) on the load behavior
for a given mill filling. A design of experimental method,
namely, central composite design, was used to provide a
series of DEM simulations that were conducted on a
two-dimensional (2D) mill. To allow the irregular parti-
cle shape to be accurately determined, a quick and accu-
rate sphere-clump method was employed in modeling
the geometrical model of irregular iron ore particles, and
the changes in the four key features with mill speed and
wave lifter profile were studied, which supplies the basis
data for lifter design in the pre-design stage.

**DEM model**

In this study, the nonlinear model, namely, no-slip
Hertz–Mindlin model, was employed to figuring the
contact force between particle systems within the software EDEM because of the accurate representation of the physical situation and less computational effort. In EDEM, any kind of irregular geometrical shape of particles can be generated as a clump composed of several touching or overlapping balls. Therefore, the contact detection between the sphere clumps is sphere-based, and therefore, the discrete element algorithm of the sphere clumps is fully available for calculating the contact forces.

According to Newton’s second law of motion, the translational and rotational motions of particle \( j \) (Figure 1) can be expressed as:

\[
\begin{align*}
\frac{d}{dt} m_j v_j &= m_g + \sum_i \left( F_{n,i,j} + F_{t,i,j} \right) \\
\frac{d}{dt} I_j w_j &= -\mu_{s,j} F_{n,j} R_j \frac{w_j}{w_j} + \sum_i R_i \times F_{t,i,j}
\end{align*}
\]

where \( m_j, v_j, w_j, \) and \( I_j \) are mass, velocity, angular velocity, and moment of inertia of particle \( j \), respectively; \( F_{n,j} \) and \( F_{t,j} \) are the total normal force and total tangential force between particle \( i \) and \( j \) given by:

\[
\begin{align*}
F_{n,i,j} &= -\frac{4}{3} E^* \sqrt{R_s \delta_n} + \frac{20}{3} \beta \left( m^* E^* \sqrt{R_s \delta_n} \right)^{1/2} v_{n,i,j} \\
F_{t,i,j} &= \min \left[ \mu_{s,j} F_{n,j} R_j \sqrt{R_s \delta_n} + \frac{8}{3} \beta \left( m^* G^* \sqrt{R_s \delta_n} \right)^{1/2} v_{t,i,j} \right]
\end{align*}
\]

where \( E^* \) is equivalent Young’s modulus, \( 1/E^* = (1 - w_i^2)/E_i + (1 - w_j^2)/E_j, E_i, E_j, \) and \( w_i \) and \( w_j \) are Young’s modulus and Poisson’s ratio of particles \( i \) and \( j \), respectively; \( R_t \) is equivalent radius, \( 1/R_t = 1/R_i + 1/R_j \), \( R_i \) and \( R_j \) are the contact radius of particles \( i \) and \( j \); \( m^* \) is equivalent mass, \( 1/m^* = 1/m_i + 1/m_j \); and \( m_i \) and \( m_j \) are the mass of particles \( i \) and \( j \); \( \delta_n \) and \( \delta_t \) are the normal overlap and tangential overlap, respectively; \( \mu_{s,i,j} \) is the coefficient of static friction between particles \( i \) and \( j \); \( v_{n,i,j} \) and \( v_{t,i,j} \) are the relative normal velocity and tangential velocity, respectively.

**Methodology**

**Mill geometry and operating conditions**

In this study, the specifications of the mill geometry, summarized in Table 1, were constructed to address the effect of mill speed and lifter height on the load behavior under the given fill level. The lifter profiles used in this study were single wave and the variation of lifter height represented the wear states from new lifters to worn lifters (wear cycle). The highest lifter had the height of 30 mm, whereas the shallowest lifter had the height of 10 mm, as shown in Figure 2.

**Table 1.** The configuration of experimental mill.

| Parameter                        | Value             |
|----------------------------------|-------------------|
| Mill diameter (m)                | 0.52              |
| Mill length (m)                  | 0.041             |
| Lifter profile                    | Single wave       |
| Number of lifters                | 12                |
| Lifter height (mm)               | 10–30 mm          |
| Mill speed (%)                   | 55%–95% of critical speed |
| Critical speed (r/min)           | 58.7              |
| Particle size (mm)               | 2 × 4 mesh        |
| Fill level (%)                   | 20                |

Due to computing considerations, there are some limitations in the current state of DEM software. In particular there are restrictions on particle size and shape that can realistically be modeled. In this work, the geometrical shapes of iron ore particles were estimated on the basis of sphere-clump method. During the DEM simulations, the average time spent on each
A numerical calculation was approximately 12 h. In the event that the optimized numbers of DEM simulations are desired, a design of experimental method, namely, central composite design, was used to minimize the number of DEM simulations and was conducted to determine the load behavior affected by mill speed and lifter worn states. In this study, for a two-parameter investigation, central composite design is an elegant method to optimize the number of simulations. For the central composite design, five different mill speeds and five different lifter heights were needed to perform on the mill. The lifter heights ranged from 10 to 30 mm and the mill speeds ranged from 55% to 95% of critical speed were selected to determine the desired intermediate values. Based on the central composite design method, 12 experimental schemes were addressed with the same filling level (20%) and the same mono-sized particle size (2\texttimes\texttimes\texttimes mesh), as shown in Table 2. Four center-point repeats, namely, 20 mm in height and 75% of critical speed in mill speed, were included to represent the simulation error.

Arguably, the key aspect of the no-slip Hertz–Mindlin model is to provide the quantitative contact parameters between particle–particle and particle–wall, that is, coefficient of restitution, the coefficient of static friction, and the coefficient of rolling friction, besides the mechanical properties of iron ore particles. Researchers found that the collision parameters were highly sensitive to some key factors such as particle shape, drop height, and material properties. Therefore, the ranges of collision parameters were obtained on the basis of different experimental methods. First, the mechanical properties of particles and liner were measured based on the testing machine (the measurement of mechanical properties of particles was repeated five times). The coefficient of restitution was estimated on the basis of drop particle tests, in which individual iron ore pellets were allowed to free-fall under gravity with the aid of a vacuum release system against a target surface. Then, the heights of rebound were recorded, and therefore, the coefficient of restitution can be calculated. The static friction coefficients were measured on the basis of pin-on-disk tribometer tester. The rolling friction coefficient between particle and liner was measured on the basis of inclination tests. The rolling friction coefficient between particle and particle was determined on the basis of the swing-arm slump test. Finally, the contact parameters were measured, and the “sand-pile calibration” was used to calibrate the measured parameters. However, in most cases, the DEM simulations were conducted using the mid-range values. In this study, the density and shear modulus of iron ore particles were 4415 kg/m$^3$ and 2.73 GPa, respectively. The particle size ranged from 8.5 to 5 mm with the average size of 6.75 mm. The restitution coefficient was 0.49, and the static friction coefficient was 0.48. The rolling friction coefficient was hard to measure quantitatively, and the result was summarized at 0.02 from the literature.

### Sphere-clump methods

In this study, the required mono-sized iron ore particles (2\times\texttimes mesh) were first sieved on the vibrating screen for different times such as 1, 3, 5, 10, 15, and 20 min. The results indicated that the mass was almost invariant after 10 min and therefore 10 min was used in this work. In mill processing, the particle shape is highly irregular because of the breakage behavior and grinding. Researchers have proposed that the sphericity was the major physical parameter to characterize the particle shape, giving

\[
\Psi = \frac{SA_{cr}}{SA_p} = \frac{\sqrt[3]{6\pi V^2}}{SA_p}
\]

where $SA_{cr}$ is real surface area of the iron ore particle and $SA_{cr}$ is the surface area of the equivalent sphere with the same volume of the real particle.

In the event that more accurate shape representation was desired, an automatic method for generating sphere-clump model of real particles was carried out to approximate the desired shape. The elegant software, named Automatic Sphere-clump Generator (ASG), was employed to realize this method for generating a geometrical model that can be used in DEM simulations. The method is divided into two steps, sphere detection.
and sphere optimization. Sphere detection is used for populating the geometrical model with suitable spheres by means of a random selection process. After the clump initialization, the Levenberg–Marquardt non-linear least-square method is carried out to optimize and minimize the distance between the clump’s surface and the original mesh. The Levenberg–Marquardt method is a standard technique used to solve nonlinear least-square problems. The Levenberg–Marquardt algorithm is the most widely used optimization algorithm. It outperforms simple gradient descent and other conjugate gradient methods in a wide variety of problems. The Levenberg–Marquardt algorithm is first shown to be a blend of vanilla gradient descent and Gauss–Newton iteration. In order to characterize the sphere clumps quantitatively, two parameters describing the error, namely, volume error and the percentage volume error (EIT error), are employed. EIT error shows the percentage average mass distribution error along the principal axes, and the volume error shows the percentage volume error. The volume error is expressed by

\[
\text{Volum error} = \left( \frac{V_m - V_c}{V_m} \right) \times 100\%
\]

where \(V_m\) is the mesh volume and \(V_c\) is the sphere-clump volume.

Assuming the mono-sized particles consisted of two typical particles, the geometrical model of iron ore particles was generated using the sphere-clump method, as shown in Figure 3.

Results and discussions

Particle shape estimation

In an attempt to represent the particle shape accurately, 20 particles are selected to determine the sphericity of \(2 \times 4\) mesh particles. The details of the physical parameters are given in Table 3. From the data in Table 3, the average sphericity calculated from the 20 particles is 0.776, which is quite irregular comparing with the sphere so that the simplifications and assumptions of irregular particle as simple spherical shape are unrealistic.

In the event that the more accurate representation and less computational effort expense are desired, the geometrical model of iron ore particle shape is conducted using the sphere-clump methods. Assuming the

![Figure 3. The geometrical model of iron ore particles (30 spheres).](image)

Table 3. The details of the physical parameters of \(2 \times 4\) mesh.

| No. | \(x\) (mm) | \(y\) (mm) | \(z\) (mm) | \(SA_{hp}\) (mm\(^2\)) | \(V\) (mm\(^3\)) | \(SA_{ae}\) (mm\(^2\)) | \(\Psi\) |
|-----|-------------|-------------|-------------|--------------------------|-----------------|--------------------------|------|
| 1   | 12.00       | 10.13       | 9.04        | 306.59                   | 371.26          | 249.76                   | 0.81 |
| 2   | 17.28       | 10.96       | 9.32        | 384.21                   | 450.97          | 284.34                   | 0.74 |
| 3   | 16.33       | 8.81        | 10.56       | 362.99                   | 417.46          | 270.08                   | 0.74 |
| 4   | 17.08       | 7.66        | 10.56       | 356.01                   | 396.36          | 260.90                   | 0.73 |
| 5   | 11.99       | 11.10       | 9.00        | 315.12                   | 386.53          | 256.56                   | 0.81 |
| 6   | 8.90        | 7.80        | 6.57        | 177.12                   | 140.36          | 130.59                   | 0.74 |
| 7   | 9.06        | 10.32       | 8.40        | 207.58                   | 184.78          | 156.86                   | 0.76 |
| 8   | 7.27        | 6.81        | 7.92        | 157.98                   | 132.59          | 125.72                   | 0.80 |
| 9   | 9.87        | 6.98        | 6.58        | 190.06                   | 172.74          | 149.97                   | 0.79 |
| 10  | 7.68        | 8.26        | 7.16        | 164.40                   | 138.55          | 129.47                   | 0.79 |
| 11  | 10.87       | 9.99        | 5.76        | 216.31                   | 198.35          | 164.45                   | 0.76 |
| 12  | 8.66        | 4.68        | 9.18        | 196.37                   | 179.84          | 154.05                   | 0.78 |
| 13  | 10.06       | 7.24        | 7.52        | 188.76                   | 165.99          | 146.04                   | 0.77 |
| 14  | 6.90        | 6.68        | 5.60        | 138.72                   | 124.48          | 120.54                   | 0.87 |
| 15  | 9.78        | 5.50        | 8.02        | 177.04                   | 145.33          | 133.65                   | 0.75 |
| 16  | 7.25        | 13.93       | 10.87       | 330.06                   | 358.60          | 244.05                   | 0.74 |
| 17  | 7.73        | 15.17       | 9.13        | 335.25                   | 350.82          | 240.51                   | 0.72 |
| 18  | 14.14       | 7.09        | 8.76        | 272.36                   | 283.56          | 208.69                   | 0.77 |
| 19  | 13.98       | 8.13        | 8.80        | 319.42                   | 409.57          | 266.66                   | 0.83 |
| 20  | 10.51       | 8.15        | 8.50        | 246.43                   | 265.33          | 199.65                   | 0.81 |
mono-sized particles consisted of two typical particles, the geometrical model of iron ore particles was generated as shown in Figure 4. Research works show that the accuracy of irregular iron ore particles increases with an increase in the number of elements. In an attempt to obtain the appropriate number of sphere clump, different numbers of sphere clump are selected and the results are summarized (Figure 4).

As can be seen in Figure 4, it is interesting to see that the accuracy in describing the geometrical shape of iron ore particles increases with an increase in the number of spheres, which will require more computational effort. Therefore, considering the accuracy in describing the shape of iron ore particles and computational effort, the appropriate sphere-clump numbers should be carefully selected on the basis of volume error and EIT error.

Figure 5 shows the volume error and the percentage average mass distribution error along the principal axes affected by the number of spheres. It is also evident from Figure 5 that the change in volume error and EIT error with number of sphere clumps decreases dramatically and then remains approximately unchanged. Once the number of sphere clump is greater than 10, the maximum volume error and EIT error are 1.1% and 1.4%, and the minimum volume error and EIT error are 0.1% and 0.2%, respectively. Hence, to achieve computational accuracy without increasing the amounts of calculation, the geometrical model used in the work is a cluster of 10 spheres.

**Key feature locations identification**

In order to describe the load behavior accurately, four key feature locations, namely, impact toe, bulk toe, shoulder, and head positions, were conducted using the visualizations of the charge shape and streak patterns. The streak patterns are the streamlines which represent the trajectory of each particle at a certain time interval. By definition, the impact toe is the location where the highest trajectories in the cataracting stream intersect the liner. The bulk toe is the location where the highest position is reached by the bulk of the particle in the toe region. The shoulder position is the location where the trajectory of particles is going to diverge from the mill. The head position is the point where the highest point of the particle trajectory that is still in contact with the liner. As is shown in left-hand side of Figure 6, the normal display of EDEM particles is employed to determine the bulk toe and shoulder position. However, the streamline display of the trajectory by tracing the particle position makes it easier to determine the impact toe and head position, as shown in right-hand side of Figure 6. The positions of these features are listed in a counterclockwise motion from six o’clock position, as shown in Figure 6.

Cases 3, 6, 9, and 12 represent the four center-point repeats conditions. There has a fine distinction between the four key feature locations because of the particle probability distributions caused by the working mechanism of DEM software. There is small difference between the impact toe and the bulk toe with the location ranged from 340 to 342. The shoulder position is located in the range of 111–113, while the head position is always above the shoulder ranged from 124 to 125. Hence, the average values are used for studying the load behavior of iron ore particles.

Figure 7 shows the influence of mill speed on the four key feature locations (impact toe, bulk toe, shoulder, and head positions) for three various lifter heights. As can be seen in Figure 7(a), the impact toe is
clearly a strong function of the lifter height. For lifter height larger than 2/3 of the new lifter, the impact toe decreases evidently with the mill speed, but for the lifter height of 12.93 mm, the impact toe is invariant with mill speed. The lifter height of 20 and 27.07 mm has the ability to throw up the particle higher than the case for the

*Figure 6.* Schematic of trajectory showing four key feature locations.

*Figure 7.* Effect of mill speed on the four key feature locations: (a) impact toe, (b) bulk toe, (c) shoulder, and (d) head.
height of 12.93 mm. Figure 7(b) presents the variation of bulk toe as a function of three different lifter heights. The bulk toe at the height of 12.93 mm is slightly higher than the case for the other height resulting in less able to slow the cascading flow of the charge down to the toe region. The bulk toe changes approximately invariant with the lifter height, and the nature of this dependence is basically the same with lifter height so that the dependence of the bulk toe on mill speed can be neglected. Figure 7(c) shows the location of the shoulder for mill speed for three various lifter heights. The change in shoulder with mill speed is approximately invariant for three different lifter heights, and the height of 20 and 27.07 mm can lift the particles higher than the case for height of 12.93 mm. Hence, the shoulder is weakly sensitive to the mill speed. Figure 7(d) presents the variation of head plotted against the mill speed. It changes approximately linear with the mill speed and moves higher as the mill speed increases. The lifter height of 20 and 27.07 mm is able to lift the head position higher than the case for the height of 12.93 mm due to the reduction in the amount of cataracting particles.

Figure 8 shows influence of lifter height on the four feature locations (impact toe, bulk toe, shoulder, and head positions) for three various mill speeds. Figure 8(a) presents the location of the impact toe for varying lifter height for three various mill speeds. The impact toe at the mill speed of 60.86% and 75% varies little with the lifter height, while it decreases linearly with an increase in the lifter height. The higher mill speed has the potential to lift the charge more higher resulting in more particles cataracting. Figure 8(b) shows the variation of the bulk toe as a function of lifter height, and the mill speed has only a weak effect on the bulk toe for three different mill speeds. Figure 8(c) presents the location of the shoulder for varying lifter height, and the shoulder increases slightly linear with the lifter height, but the difference of three curves is approximately the same. Figure 8(d) presents the variation of head plotted against the lifter height. It is evident that the head increases linearly with an increase in the lifter height, and there is a strong sensitive to the variation of mill speed. The charge can be lifted higher with higher lifter height as well as the higher mill speed.
As shown in Figures 7 and 8, the results can be used to comprehend the load behavior under various wear statuses of wave liner. Besides, the determination of four features can help us install the acoustic sensor and acceleration transducer for measuring the charge motion in the proper position in the industrial mill and experimental setup. The DEM simulations in this study can be well employed in optimizing the wave liner design in the pre-design stage.

To sum up, based on the correlation analysis, the relationship between the four key features and input parameters is addressed. The dependence of the impact toe on mill speed is higher than its dependence on the lifter height with a correlation of -0.923, which means increasing the mill speed decreases the position of impact toe. The correlation of the dependence of the head on mill speed is 0.97, which is slightly higher than the dependence on the lifter height with the correlation of 0.875. Once the lifter height has been worn out outweighing 2/3 of the new lifters, the influence will become meaningless. The shoulder changes approximately invariant with the mill speed. The dependence of the shoulder on lifter height is slightly higher than its dependence on the mill speed. The bulk toe of particles appears to be invariant to the mill speed as well as the lifter height, resulting in the approximately same inclination of the chord joining the shoulder and bulk toe. It is interesting that varying the mill speed over the range considered does not lead any obvious variation in the four key features once the lifter has worn out over two-thirds. Correspondingly, the ball mill has to replace the worn lifters. Therefore, determining the impact of mill speed and lifter on the load behavior of iron ore particles in a ball mill not only potentially facilitates the improvement in high-performance liners but also optimizes the mill speed in the pre-design stage.

Conclusion

In this study, the sphere-clump method is employed to determine the geometrical shape of the mono-sized (2 × 4 mesh) iron ore particles. The average sphericity calculated from the 20 particles is approximately 0.776, which means quite irregular comparing with the sphere so that the simplifications and assumptions of irregular particle as simple spherical shape are unrealistic. Based on the sphere-clump method, the three-dimensional (3D) shape of iron ore particles with a cluster of 10 spheres not only represents the geometrical shape trustworthy but also decreases the computational effort evidently. Subsequently, a design of experimental method, namely, central composite design, is employed to determine a series of DEM simulations. The influences of lifter height and mill speed on the impact toe, bulk toe, shoulder, and head position are determined to assess their impact on the load behavior of iron ore particles in a ball mill. The impact toe and head are highly sensitive to mill speed and filling. With an increase in the mill speed and lifter height, the impact toe decreases approximately linear, while the head increases evidently. However, the impact of mill speed plays a primary role on impact toe and head that is the case for the lifter height. The shoulder changes approximately invariant with the mill speed and varies little with the lifter height. The bulk toe of particles appears to be invariant to the mill speed as well as the lifter height, resulting in the approximately same inclination of the chord joining the shoulder and bulk toe. It is interesting that varying the mill speed over the range considered does not lead any obvious variation in the four key features once the lifter has worn out over two-thirds. Correspondingly, the ball mill has to replace the worn lifters. Therefore, determining the impact of mill speed and lifter on the load behavior of iron ore particles in a ball mill not only potentially facilitates the improvement in high-performance liners but also optimizes the mill speed in the pre-design stage.

Acknowledgements

The authors thank the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD) and the Top-notch Academic Programs Project of Jiangsu Higher Education Institutions (TATP).

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The research reported here was supported by the National Nature Science Foundation of China (Grant no. 51475458), the Jiangsu Postgraduate Scientific Research and Innovation Projects, and the Program for Changjiang
References

1. Bbosa LS, Govender I, Mainza AN, et al. Power draw estimations in experimental tumbling mills using PEPT. Miner Eng 2011; 24: 319–324.

2. Govender I, McBride AT and Powell MS. Improved experimental tracking techniques for validating discrete element method simulations of tumbling mills. Exp Mech 2004; 44: 593–607.

3. Bbosa LS, Govender I and Mainza A. Development of a novel methodology to determine mill power draw. Int J Miner Process 2016; 149: 94–103.

4. Owen P and Cleary PW. The relationship between charge shape characteristics and fill level and lifter height for a SAG mill. Miner Eng 2015; 83: 19–32.

5. Maleki-Moghaddam M, Yahyaei M and Banisi S. A method to predict shape and trajectory of charge in industrial mills. Miner Eng 2013; 46: 157–166.

6. Rezaeizadeh M, Fooladi M, Powell MS, et al. A new predictive model of lifter bar wear in mills. Miner Eng 2010; 23: 1174–1181.

7. Morrell S. The prediction of power draw in wet tumbling mills. PhD Thesis, University of Queensland, Brisbane, QLD, Australia, 1993.

8. Powell MS and Nurick GN. A study of charge motion in rotary mills Part 1—extension of the theory. Miner Eng 1996; 9: 259–268.

9. Govender I, Cleary PW and Mainza AN. Comparisons of PEPT derived charge features in wet milling environments with a friction-adjusted DEM model. Chem Eng Sci 2013; 97: 162–175.

10. Morrison AJ. Using Positron Emission Particle Tracking (PEPT) to investigate the motion of granular media in a laboratory-scale tumbling mill. Master's Dissertation, University of Cape Town, Cape Town, South Africa, 2012.

11. Govender I and Powell MS. An empirical power model derived from 3D particle tracking experiments. Miner Eng 2006; 19: 1005–1012.

12. Rezaeizadeh M, Fooladi M, Powell MS, et al. Experimental observations of lifter parameters and mill operation on power draw and liner impact loading. Miner Eng 2010; 23: 1182–1191.

13. Banisi S and Hadizadeh M. 3-D liner wear profile measurement and analysis in industrial SAG mills. Miner Eng 2007; 20: 132–139.

14. Powell MS, Weerasekara NS, Cole S, et al. DEM modelling of liner evolution and its influence on grinding rate in ball mills. Miner Eng 2011; 24: 341–351.

15. Cleary PW. Charge behaviour and power consumption in ball mills: sensitivity to mill operating conditions, liner geometry and charge composition. Int J Miner Process 2001; 63: 79–114.

16. Kalala JT, Bwalya MM and Moys MH. Discrete element method (DEM) modelling of evolving mill liner profiles due to wear. Part I: DEM validation. Miner Eng 2005; 18: 1386–1391.

17. Makokha AB, Moys MH, Bwalya MM, et al. A new approach to optimising the life and performance of worn liners in ball mills: experimental study and DEM simulation. Int J Miner Process 2007; 84: 221–227.

18. Wang D, Servin M, Berglund T, et al. Parametrization and validation of a nonsmooth discrete element method for simulating flows of iron ore green pellets. Powder Technol 2015; 283: 475–487.

19. Moreno-Atanasio R. Energy dissipation in agglomerates during normal impact. Powder Technol 2012; 223: 12–18.

20. Grima AP and Wypych PW. Investigation into calibration of discrete element model parameters for scale-up and validation of particle-structure interactions under impact conditions. Powder Technol 2011; 212: 198–209.

21. Podczeck F and Newton JM. The evaluation of a three-dimensional shape factor for the quantitative assessment of the sphericity and surface roughness of pellets. Int J Pharmaceut 1995; 124: 253–259.

22. Barrios GKP, de Carvalho RM, Kwaade A, et al. Contact parameter estimation for DEM simulation of iron ore pellet handling. Powder Technol 2013; 248: 84–93.

23. Majidi B, Azari K, Alamdari H, et al. Simulation of vibrated bulk density of anode-grade coke particles using discrete element method. Powder Technol 2014; 261: 154–160.

24. Majidi B, Melo J, Fafard M, et al. Packing density of irregular shape particles: DEM simulations applied to anode-grade coke aggregates. Adv Powder Technol 2015; 26: 1256–1262.

25. Marigo M and Stitt EH. Discrete element method (DEM) for industrial applications: comments on calibration and validation for the modelling of cylindrical pellets. Kona Powder Part J 2015; 32: 236–252.

26. Zhou YC, Wright BD, Yang RY, et al. Rolling friction in the dynamic simulation of sandpile formation. Physica A 1999; 269: 536–553.

27. Chen H, Liu YL, Zhao XQ, et al. Numerical investigation on angle of repose and force network from granular pile in variable gravitational environments. Powder Technol 2015; 283: 607–617.

28. Gibson LTM, Gopalan B, Pisupati SV, et al. Image analysis measurements of particle coefficient of restitution for coal gasification applications. Powder Technol 2013; 247: 30–43.

29. Hastie DB. Experimental measurement of the coefficient of restitution of irregular shaped particles impacting on horizontal surfaces. Chem Eng Sci 2013; 101: 828–836.

30. Dong H and Moys MH. Measurement of impact behaviour between balls and walls in grinding mills. Miner Eng 2003; 16: 543–550.