Discrete element method modelling of liner wear in dry ball milling

by J.T. Kalala* and M.H. Moys*

Synopsis

Energy consumption and wear of grinding media and liners are the major cost factors in milling plants. Since the beginning of the last century, much effort has been directed at the prediction of the power draw as affected by the mill operating conditions. This paper explores the prediction of the liner wear using the discrete element method (DEM). A mathematical model taking into account adhesion, abrasion and impact wear which occur in dry mills is derived in order to predict the loss of material on liners. The mathematical model is implemented in the DEM code using an objective function in order to produce realistic simulated profiles. Our DEM simulated predictions are compared to published experimental and industrial data.

Keywords: modelling; discrete element method; liner wear

Introduction

Liner profiles influence the load behaviour in tumbling mills and consequently the milling performance. However, due to ball and particle collisions with liners in mills, liners wear and change profiles. The grinding performance will correspondingly change over the useful life of the liners. Simulating the evolving liner profiles due to wear and quantifying the change in mill performance will therefore contribute to:

- Making the choice of the best liner design that optimizes the mill performance over its useful life
- Determining the optimal lifter replacement time
- Reducing the mass of worn liners at the end of their life.

The starting point of the prediction of the wear of lifters is the accurate prediction of the load behaviour in mills and energies involved in ball-particle–liner collisions. Since the beginning of the last century, many studies have been performed in order to improve our understanding of the mill load behaviour and its efficiency. Recently, Mishra and Rajamani (1992) applied the discrete element method to the tumbling mill problem. Since then, this method gained considerable success due to its ability to simulate the load behaviour and predict the power draw as affected by the mill speed, the mill filling, the charge composition and the liner design (Moys *et al.*, 2000; Cleary, 2001). This method has also great potential for the design of grinding mills, in the modelling of the wear of lifters (Qiu *et al.*, 2001) and the breakage of particles.

Despite the importance of modelling the wear of lifters, few papers related to the topic (Radziszewski, 1993; Glover and de Beer, 1997; Cleary, 1998; Qiu *et al.*, 2001) have been found in the literature. This is justified by the complexity of the wear phenomenon and the inability to accurately predict: (i) the mill load behaviour, (ii) the forces and energies involved in collisions of balls, particles and liners.

Two problems emerge from the review of published papers: firstly, mathematical models used to predict the wear of lifters do not take into account all types of wear that occur in the milling environment. Secondly, simulated profiles must have the same characteristics as observed practically. In this paper, both problems are tackled in order to produce realistic results. Our simulated results are compared to published experimental and industrial data.

The discrete element method

The discrete element method, initiated by Cundall and Strack (1979), is defined as a numerical method capable of simulating the motions and interactions of individual particles in a dynamic environment such as tumbling mills, fluidized-beds, chutes, etc.

* *School of Process and Materials Engineering, University of the Witwatersrand, Johannesburg, South Africa.*

The particle-particle and particle-liner interactions in a mill are modelled, in the present investigation, by the linear spring-slider-dashpot model. The spring accounts for the repulsive force, which depends on the stiffness K of the material. The slider accounts for the motion between surfaces characterized by the coefficient of friction μ. The dashpot, represented by the damping coefficient C, dissipates a proportion of the relative kinetic energy in each collision.

The normal (F_n) and tangential (F_t) forces for each interaction are given by:

$$F_n = K_n \Delta x + C_n v_n \quad [1]$$

$$F_t = \min\left(\mu F_n, K_t \int v_t dt + C_t v_t\right) \quad [2]$$

where:

K_n and K_t are respectively the normal and tangential stiffness.

Δx is the particle overlap. The maximum overlap is determined by the value of K_n. Average overlaps of 0.1–1% are desirable.

v_n and v_t are respectively normal and tangential relative velocities.

C_n and C_t are respectively, the normal and tangential damping coefficient.

C_n depends on the coefficient of restitution ε defined as the ratio of the normal component of the relative velocity after and before the collision.

$$C_n = -2\ln(\varepsilon)\frac{\sqrt{m_{ij}K_n}}{\sqrt{\pi^2 + \ln^2(\varepsilon)}} \quad [3]$$

where m_{ij} is the reduced mass of two particles i and j defined by:

$$m_{ij} = \frac{m_i m_j}{m_i + m_j} \quad [4]$$

The DEM is able to simulate the load behaviour in mills and quantify interactions between media and liners in terms of forces and energy involved in collisions. It is therefore an appropriate tool to model the evolving lifter profiles due to wear.

Mathematical model of wear

The mathematical wear model used in order to predict the volume of material removed on liners must take into account all the types of wear that occur in the milling environment. In dry milling, the following types of wear occur: adhesive, abrasive and impact. Each of these types has been modelled in order to predict the volume removed.

Archard (1953) developed a simple model of adhesive wear. He found that when two surfaces in contact slide over each other, the volume removed V is directly proportional to the normal load P, the sliding distance S, and inversely proportional to the hardness H of the worn surface. Mathematically:

$$V = \frac{KSP}{H} \quad [5]$$

Where K is the wear coefficient depending on material properties.

Rabinowicz (1965) derived the following equation for abrasive wear.

$$V = \frac{PS\tan\theta}{H\pi} \quad [6]$$

Where θ is the angle of attack of the abrasive material.

It can be seen that the Archard and Rabinowicz equations are similar, with K in the Archard equation equal to $\frac{\tan\theta}{\pi}$ in the Rabinowicz equation. Therefore, adhesion and abrasion wear can be represented by the single Archard equation rewritten in the following form:

$$V = WE_{ad-abr} \quad [7]$$

where W is the wear rate equal to K/H

E_{ad-abr} is the adhesion/abrasion energy

If there is no relative motion between media and liners in contact (the sliding $S = 0$), Archard's equation will predict no wear. This situation shows the limitation of the Archard model to predict wear in a situation where there is only impact without sliding.

Studies of repetitive impact wear by Wellinger and Breckel (1969) and Hutchings (1992) show that the volume of material removed V is proportional to the impact velocity according to the following equation:

$$V \propto Kv^n \quad [8]$$

They found experimentally that the velocity exponent n varies from 1.5 to 2.4 according to the material tested. We use the theoretical value 2.

As energy and velocity are related ($E = \frac{mv^2}{2}$), Equation [8] can be rewritten into the following form:

$$V = KE_{impact} \quad [9]$$

Assuming that the total wear occurring on a surface i is the sum of adhesion/abrasion and impact wear, we deduce the following equation:

$$V_i = W\left(a_{ad-abr} * E_{ad-abr,i} + a_{impact} * E_{impact,i}\right) \quad [10]$$

Where

V_i is the volume of material removed on a surface i

W is the wear rate

a_{ad-abr} and a_{impact} are weight factors given to adhesion/abrasion and impact energy, depending on material properties.

$E_{ad-abr,i}$ and $E_{impact,i}$ are adhesion/abrasion and impact energies dissipated on surface i

Modelling of the evolving lifter profile

To implement our wear Equation [10] in our DEM code and removed material on liners we need to discretize our liner in small surfaces. The vertical discretization presented in Figure 1 is the simplest.

It is experimentally recognized that worn profiles tend to be 'smooth'; in other words, the difference of two consecutive slopes of worn profiles is small. To take into account this factor, we have defined an objective function S^2 with components: S_1^2, S_2^2, S_3^2, S_4^2 which have the following functions:

➤ S_1^2 minimizes for each segment the difference of volume predicted by our wear model and the volume calculated from measurements

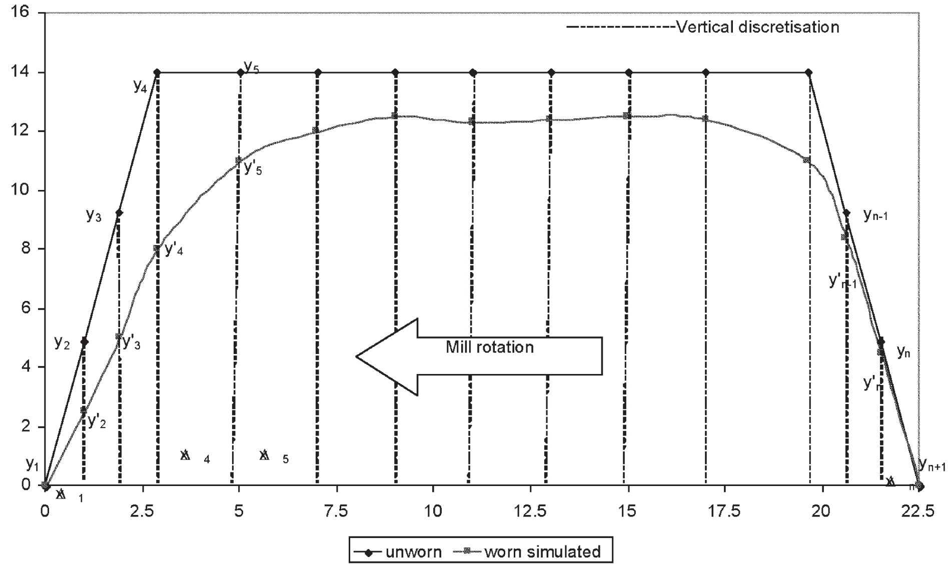


Figure 1—Vertical discretization of a trapezoidal lifter

- S_2^2 minimizes the difference of two consecutive slopes of the worn profile (in order to get a smooth profile)
- S_3^2 minimizes the difference of slope between the unworn and the worn profile (so that there is no large change of profile between the worn and the unworn profile)
- S_4^2 maintains a steadily decreasing profile height at any longitudinal position by penalizing heavily any tendency for y' to increase with time.

Mathematically we have:

$$S^2 = S_1^2 + \lambda * S_2^2 + \alpha * S_3^2 + S_4^2 \quad [11]$$

Where λ and α are weight factors which decide the importance to give to S_2^2 and S_3^2 respectively.

For the vertical discretization, the objective function is given by:

$$S^2 = \sum_{i=1}^{n}\left(\frac{(y_i - y_i') + (y_{i+1} - y_{i+1}')}{2}\Delta x_i * L - V_i\right)^2 + \lambda\sum_{i=1}^{n-1}\left(\frac{y_{i+2}' - y_{i+1}'}{\Delta x_{i+1}} - \frac{y_{i+1}' - y_i'}{\Delta x_i}\right)^2 + \alpha\sum_{i=1}^{n}\left(\frac{y_{i+1} - y_i}{\Delta x_i} - \frac{y_{i+1}' - y_i'}{\Delta x_i}\right)^2 + \sum_{i=1}^{n+1} e^{\beta(y_i' - y_i)} \quad [12]$$

where

n is the number of segments of the discretized lifter

y_i is the ordinate of the initial position of the lifter profile with $i = 1$ to $n + 1$

y_i' is the ordinate of the worn lifter profile with $i = 1$ to $n + 1$

L is the mill length

Δx_i is the width of the element i with i = 1 to n

V_i is the predicted volume removed by our wear equation on the element i with $i = 1$ to n

β is a large number (more than 1 000), so that y_i' is always less than y_i

The ordinates y_i' of the worn lifter profile are found after minimization of the objective function ($\frac{\partial S^2}{\partial y_i'} = 0$).

Laboratory experimental equipment and industrial mill liner profiles

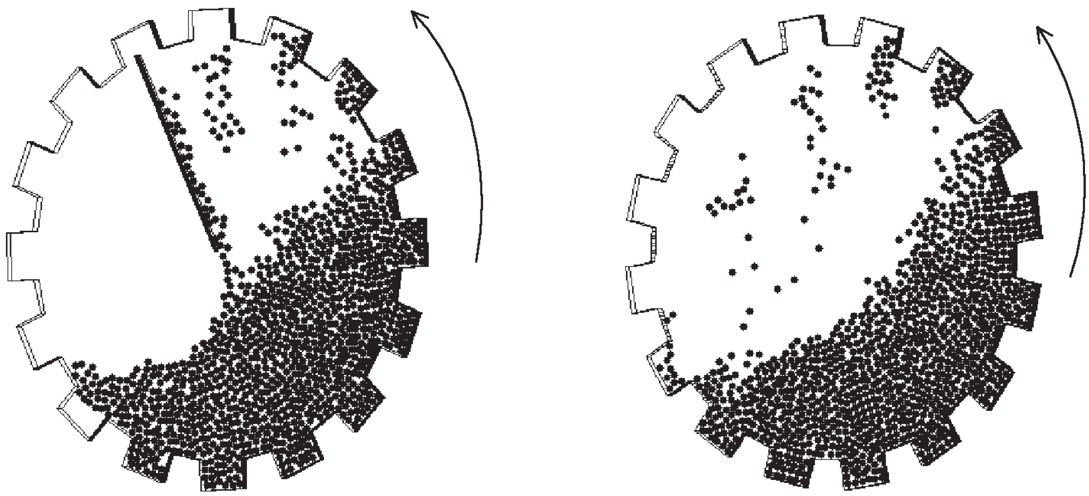
Valderrama *et al.* (1996) performed tests of measurement of the wear of lifters in a laboratory ball mill. The object of those tests was to study the role of cascading and cataracting motion of balls on the wear of liners. They used a mill having a diameter of 0.28 m and a length of 0.11 m. The mill was filled at 30% by volume with balls of 0.0045 m diameter. The mill was equipped with 16 equally spaced lifters made in quick wearing ceramic. To distinguish the effect of cascading from the effect of cataracting, the laboratory mill was modified to allow the incorporation of a deflector plate, which prevents the cataracting motion of balls. Figure 2 shows the DEM simulated load behaviour at 75% of critical speed in the presence and absence of a deflector respectively.

It can be seen from Figure 2 that without the deflector, balls are cataracting directly on liners while with deflector, the cataracting motion is prevented.

Industrial data of measured mill liner profiles have been provided by eskom Lethabo power station (South Africa). Tumbling mills are used for the grinding of coal in dry conditions. The characteristics of these mills are reported in Table I. They are equipped with double wave lifters. Only data of the unworn lifter and worn out lifter profile after 57 726 hours have been provided.

Results and discussions

Figures 3 and 4 show the comparison between Valderrama *et al.* (1996) laboratory experimental measurements and DEM simulated results. The tests have been conducted for a percentage filling of 30% by volume at 75% of critical speed in the presence and the absence of the deflector. The lifter profiles were measured every 10 minutes and each



(a) (b)

Figure 2—DEM simulated load behaviour at 75% of critical speed with (a) and (b) without the deflector

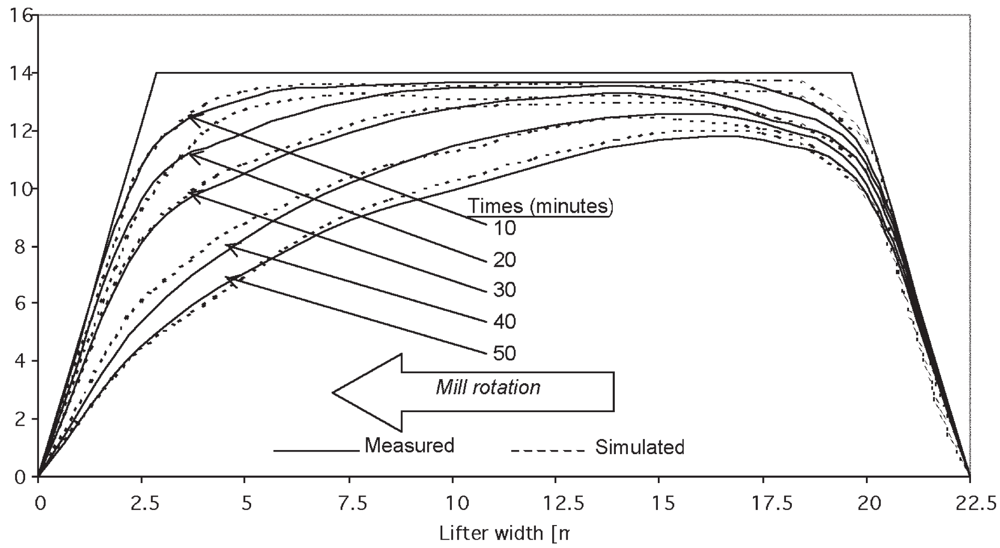


Figure 3—Comparison between measured (Valderrama *et al.*, 1996) and simulated wear profiles. Mill diameter D = 0.28 m, percentage of filling J = 30%, ball diameter d = 4.5 mm, critical speed Nc = 75%, lifter front angle = 25 degrees, in the presence of the deflector

Table I

Characteristics of the ESKOM Lethabo mill

Mill diameter to the shell	4267 mm
Mill Length	5790 mm
Mill speed	15.7 rpm
Percentage of filling	24.2%
Top ball size dimension	50 mm
Number of circumferential lifters	30

measurement is the average of 9 to 16 test lifters. It can be seen from Figure 3 that at 75% of critical speed in the presence of the deflector, most of the wear occurs at the front of the lifter, while from Figure 4 most of the wear occurs not only at the front of the lifter but also on the top due to cataracting balls. The lifter height decreases sensibly in the absence of the deflector. The volume of material removed in the absence of the deflector is higher than in the presence of the deflector.

A good agreement has been found between the measured and our DEM predictions at different steps.

The results of the DEM simulation involving the ESKOM Lethabo double wave lifter profile is presented in Figure 5. Having only the unworn and the worn lifter profiles, we used a constant wear rate and parameters in the wear model to predict the worn profile from the unworn. The wear rate chosen allows reaching the worn profile in 8 steps. The last simulated profile is in good agreement with the worn profile measured after 57 726 hours.

The lifter was vertically discretized in 42 equally spaced divisions. DEM predictions of impact and abrasion energies dissipated on the discretized lifter divisions as a function of time are represented in the same figure. Lifter divisions 4 to 8 for the first lifter wave and 26 to 30 for the second lifter

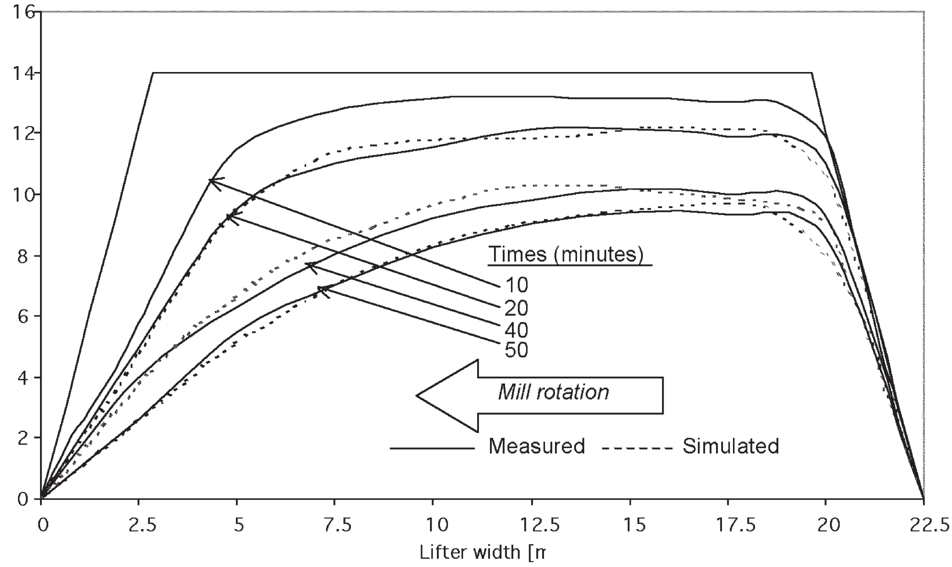


Figure 4—Comparison between measured (Valderrama *et al*, 1996) and simulated wear profiles. Mill diameter D = 0.28 m, percentage of filling J = 30%, ball diameter d = 4.5mm, critical speed Nc = 75%, lifter front angle = 25 degrees, without the deflector

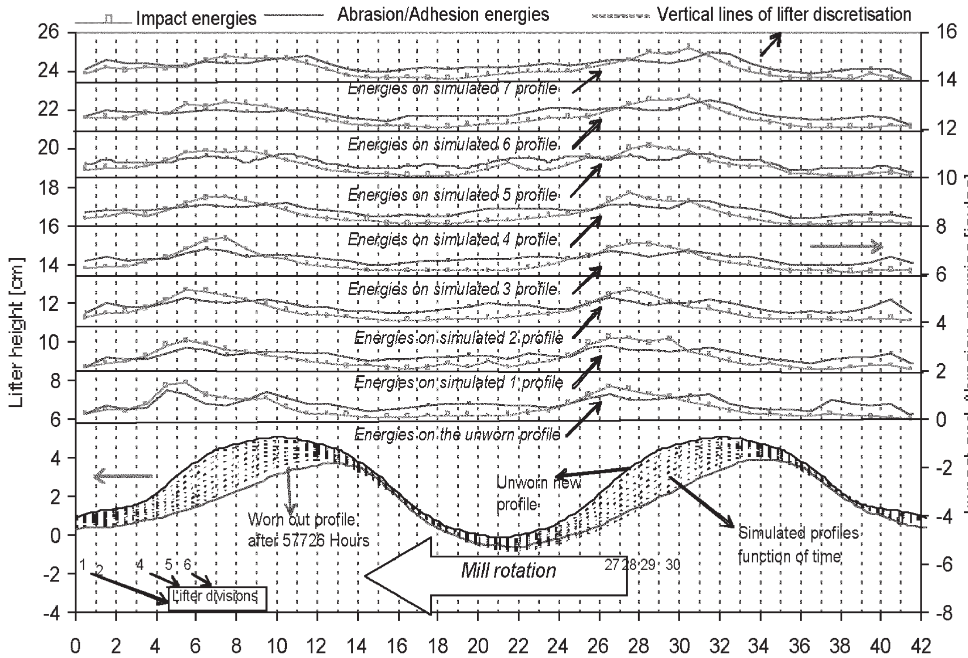


Figure 5—Modelling of evolving double wave lifter profile used at Lethabo power station

wave constitute the front of the unworn profile. As the lifter profiles evolve, the front of the lifter is changing. It can be seen from the figure that the impact energy is always higher than the abrasion energy at the front of lifter profiles and the opposite at the back. These results are in agreement with the observation of the simulated load behaviour in the mill where it can be seen that most of impacts occur at the front of the lifter waves, while at the back, balls are sliding.

The simulated Lethabo mill load behaviour as a function of time is represented by Figure 6. Not much difference is observed between the load behaviour simulated for the unworn lifter and the worn-out profile after 57 726 hours as the double wave lifter profiles conserve almost the same profile. The general trend indicates, nevertheless that as the lifter is wearing, we have less cataracting particles in the mill. The less particles cataract in the mill, the fewer they are exposed to the air, which removes particles from the mill. In this case, liners are removed from the mill not because of the drop in milling performance but because they reach a critical thickness susceptible to breakage. The results predicted confirm the observations at the industrial scale.

Conclusions

We show that the discrete element method is able to predict the evolving mill lifter profiles due to wear. To achieve

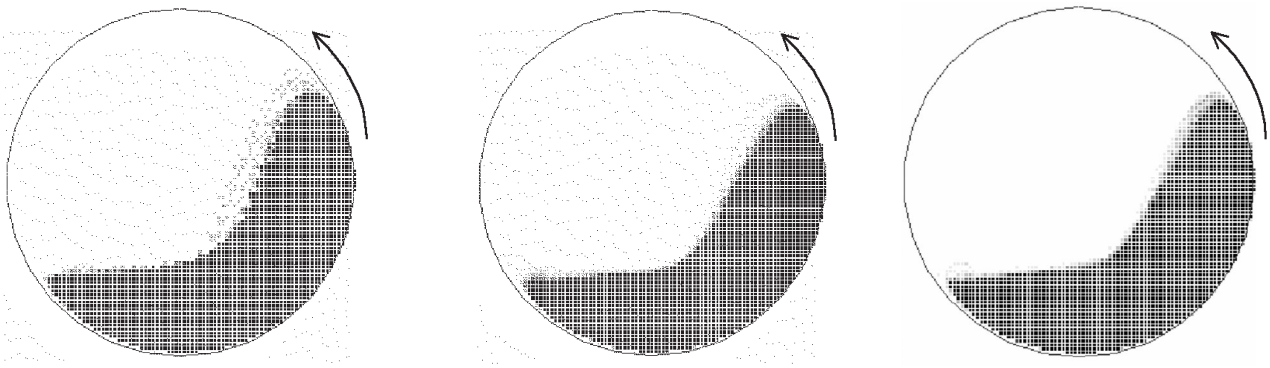


Figure 6—Simulated particles density plot (PDP) in the Lethabo mill as a function of time

accurate predictions, it was required to use a mathematical model of wear that takes into account all types of wear occurring in the mill environment and also to use an objective function producing realistic profiles.

From the laboratory experimental data studying the effect of cataracting balls on the wear of lifters, we show that the lifter volume lost due to wear is higher without the deflector due to cataracting balls impacting directly on lifters. The contribution of impact energies on the wear of lifters is higher without the deflector.

From our predictions of Eskom Lethabo double wave lifter profile evolving due to wear, we study the effect of the variation of the profile on the load behaviour. Our understanding of the relationship between liner profile and load behaviour has been improved.

Acknowledgements

The authors would like to thank:

- Professor Waldo Valderrama for providing the experimental data of the worn lifter
- Murray Bwalya for the development of the Wits DEM software
- Eskom for the authorization to publish data related to their tumbling mill.

References

ARCHARD, J.F. *Journal of applied phys.*, vol. 24. 1953. pp. 981–988.

CLEARY, P.W. Predicting charge motion, power draw, segregation and wear in ball mills using discrete element methods. *Minerals Engineering*, vol. 11, no. 11, 1998. pp. 1061–1080.

CUNDALL, P.A. and STRACK, O.D.L. A discrete numerical model for granular assemblies, *Geotechnique*, vol. 29, no. 1, 1979. pp. 47–65.

GLOVER, G.and DE BEER, J.C.K. The application of the discrete element method to the optimisation of mill liner systems. *Proceedings of the XX IMPC-Aachen*, 21–26 September, 1979.

HUTCHINGS, I.M. Tribology, *friction and wear of engineering materials,* London. 1992.

MISHRA, B.K. and RAJAMANI, R.K. *Applied Mathematical Modelling*, vol. 16, no. 598. 1992.

MOYS, M.H., VAN NIEROP, M.A., GLOVER, G., and HINDE, A.L. A discrete element method investigation of the charge motion and power draw of an experimental two-dimensional mill. *Int. J. Miner. Process*. vol. 61, 2001. pp. 77–92.

RABINOWICZ. *Friction and wear of materials,* John Wiley, New York. 1965.

RADZISZEWSKI, P. Simulation of ball charge and liner wear. *Wear,* vol. 169, 1993. pp. 77–85.

QIU, X., POTAPOV, A., SONG, M., and NORDELL, L. Prediction of wear of mill lifters using discrete element method. *Int. AG and SAG Grinding Technology*, vol. IV. 2001.

VALDERRAMA, W., MAGNE, L., MOYANO, G., SANTANDER, C., and PONTT, J. The role of cascading and cataracting in mill linear wear. *Int. AG and SAG Grinding Technology*, vol. III. 1996.

WELLINGER, K. and BRECKEL, H. Wear, vol. 13, 1969. pp. 257–281. ◆