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Experimental Study on the Wear of Liner in Tumbling Mill under Dry and Wet Conditions

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ABSTRACT: Lifters/liners worn in tumbling mill and consequently their dimensions change during the course of operation. These changes in dimensions have a significant influence on the overall economic performance of the mills. In this project, the influences of slurry filling and slurry concentration on the wear of lifters were investigated using a pilot mill of 1m diameter and 0.5m length. Copper ore with a size smaller than one inch was used to prepare slurry at 40%, 50%, 60%, 70%, and 80% solids concentration of mass. The tests covered a range of slurry filling from 0.5 to 2.5 with ball filling at 20% and mill speeds at 75%. The mill grinding mechanism in this pilot mill is a combination of both impact and abrasion mechanisms. It was found that the lifters' wear rises with the increase of feed filling in the mill under dry conditions. During the wet condition, when there is an increase in the slurry filling and slurry concentration, the wear decreases. In wet grinding, the relative velocity between the materials and the lifters is more than in the dry mode and the wear is 1.5–3 times greater than in the dry condition.

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1- Introduction

Tumbling mills include a rotary cylindrical pipe of 2.5-12m diameter and a length of 3-8m, made of steel plates and reaching up to 22MW consumption power. Inside a mill, materials change from large dimensions into small ones due to impact and abrasion processes. For wear protection, the inner surface of the mill is covered by the liner. Mills work in the two forms of dry and wet. The wear of liners affects the mill performance because of the loss of lifting. In addition, the substitution of worn lifters takes a substantial amount of time and energy for technicians. Besides, unsystematic breakage and the lifters replacement would cause several undesirable downtimes of the mill. Along these lines, the acknowledgment of the wear may improve the productivity of the factory [1, 2]. The mechanisms (or processes) of wear are categorized into the following five types: adhesive wear, abrasive wear, surface fatigue, fretting wear, and erosive wear [3, 4]. Additionally, it ought to be noticed that corrosion happens especially in the wet grinding. Fig. 1 [5] shows the load behavior in a wet Semi-Autogenous Grinding (SAG) mill.

For the prediction of the lifter/liner wear, different methods have been proposed. Wear models are developed in order to determine how a ball charge size distribution and liner profiles change as a result of wear [6, 7]. Cleary [8] has explained how the Discrete Element Method (DEM) could be used for wear prediction. Kalala et al. [9] studied the wear of lifter profiles in dry coal grinding mills. In order to measure the mass loss that occurred due to the wear in a real SAG mill, Banisi, Yahyaei, and Hadizadeh [10, 11] employed a mechanical lifter wear monitor.

In order to examine the forces in the mill charge region, a theoretical model was exploited by Rezaeizadeh et al. [12]. They employed the DEM model to compute the balls' velocity profile in the mill. In another work carried out by Rezaeizadeh et al. [13], an experimental mill with the possibility of performing under both dry and wet conditions was conducted to investigate the influence of mill speed, ball filling, size of ore, and the material of the lifters on the wear. Also, Radziszewski et al. [14, 15] have proposed an equation for mass loss in a tumbling mill.

The previous results showed that nothing happed within a laboratory ball mill and this has the right to be depicted as an effective impact on the wear. In a laboratory ball mill, the impingement velocities and energies are extremely little to cause any specific impact-related damage to mechanisms such as dynamic stress-wave micro-fracture [16, 17] and all of the damage and wear which was observed is abrasive.

The wear of lifters in this work is due to a combination of corrosion, impact, and abrasive wear. In the case of impact loading, one can refer to the research of Hatami et al. [18-20]. But less research has been done on impact

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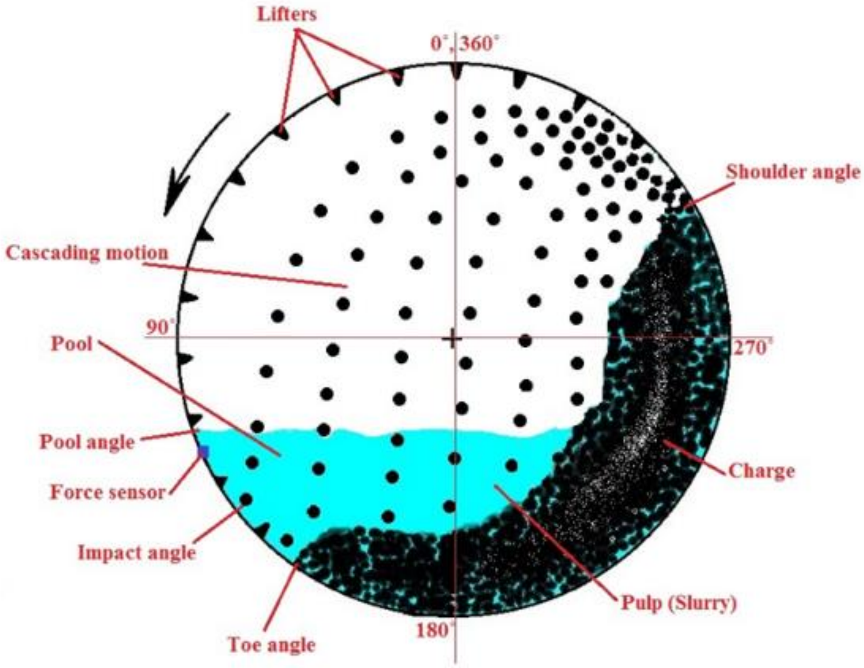

Fig. 1. Definition of the load behavior in a wet tumbling mill [5].

Fig. 2. Pilot mill.

wear. It is important to note that a few studies have been published to assess the wear of lifters in tumbling mills under wet conditions and the available data in this area are rather limited and scarce [21]. In this work, the black box model is used to study the effects of operational parameters such as slurry filling and slurry concentration on the wear of lifter/liner in a tumbling mill in both dry and wet conditions.

2- Experimental Method

The experimental pilot mill is shown in Fig. 2. There are 15 lifters with 50mm height and a face angle of 30˚. In the current work, the combination of the balls (40% of the balls with 60mm diameter, 40% of the balls with 40mm diameter, and 20% of the balls with 25mm diameter) was used as grinding media with 20% of the total volume of the mill. The speed applied for this study was 75% of the critical speed. In

Table 1. Mill characteristics and grinding conditions.

Mill		
	diameter	1000 mm
	length	500 mm
	speed	31 rpm
	fraction of critical speed (*Φc*)	0.75
Lifters		
	number	15
	height	50 mm
	face angle	30 degree
	shape	trapezoid, leg thickness 50 mm
Grinding media		
	material	chrome alloy steel
	ball diameter	40% of the balls with 60mm, 40% of the balls with 40mm, and 20% of the balls with 25mm diameter
	density	7800 kg/m^3
	ball filling (*Jb*)	0.2 fraction of mill volume
	total ball mass	352 kg
Feed		
	material	copper ore
	particle size	$F_{100} = 25.4$, $F_{80} = 12.7$, $F_{50} = 8$ and $F_{10} = 0.3$mm
	ore density	2700 kg/m^3
	slurry concentration (*C*)	0.4, 0.5, 0.6, 0.7, and 0.8 (mass fraction of solid in slurry)
	slurry concentration	20, 27, 35, 46, and 60 (vol.% solid)
	slurry density	1340, 1460, 1610, 1790, and 2010 kg/m^3
	slurry filling (*U*)	*U*=0.5 - 2.5 (as the volume fraction of ball bed voidage)

Table 1, the mill characteristics and grinding conditions are listed. To investigate the impact forces, a quartz force sensor mounted through the mill wall was employed to measure the impact force on the lifter. The load cell is mounted on the liner plate. The output signal from the quartz sensor was calibrated to check or record impact forces. The impact sensor has a threshold sensitivity of 48.8 N.

The feed of the mill is copper ore with a size smaller than 25.4mm, which F_{80} and F_{50} of them are 12.7 and 8mm, respectively. The slurry concentration (*C*) used in the tests was 40%, 50%, 60%, 70% and 80% (mass % solid). Moreover, to investigate the influence of slurry filling (*U*) on the wear, the amount of slurry is increased until the slurry volume becomes 2.5 times the ball's bed voidage. The concept of slurry filling in the mills was first introduced by Austin et al. [22].

In order to investigate the wear, the wear specimens are installed in two of the lifters. These lifters have a special location for the specimen placement which was able to protect the specimens. The specimens are mounted in a slot on the top of the lifters and were screwed in their places (Fig. 3). The specimens were made from ductile steel. To prevent overheating and the variation of the surface properties, during their production, cold-working processes were used. To enhance the surface finishing, the specimens were completely polished. Sample size has no effect on wear rate. In order to assess the effect of size and shape of the specimens, one of them was chosen with a larger initial mass of 150g and with a larger size, and the other one with 88g with a smaller size. Since the density of the lifters is constant, as a result, the mass difference between them can be a suitable criterion for the wear measurement. Thus, to measure the wear rate, the masses of specimens are quantified before taking the test by an accurate scale (GR-200) with the precision of 0.1mg. After the test, the specimens are weighed again. Using the ratio of mass variation to the initial mass, the wear rate can be obtained. For each experimental condition, the mill is allowed to rotate for 15 minutes, and then the specimens take the mill out to weight and the rate of wear is calculated. The results are multiplied by 4 to obtain the wear rate in 1/hr. During the experiments ,the slurry temperature was regularly checked and the changes were shown between 20-23˚C.

The results of 15 different experiments which assessed the effects of the mill condition in a wet and dry mode such as feed filling, slurry concentration, and slurry filling on the wear of liners are presented in the next sections. All experiments are repeated (totally 30 tests) and 2000kg of ore and 1000lit of water (totally 3 tons) were used in all of the tests. In order to measure the experimental error, one experiment was repeated three times, and their variability is seen to be within ±0.00002 1/hr at a 98% confidence level.

Fig. 3. Specimens and holder lifters of specimens.

3- Results and Discussion

In a pilot mill with a 1m diameter, in cascading motion, the ball velocity rapidly approaches 4m/s and it impacts at high speed in the toe region [12]. The kinetic energy of the balls with 60mm diameter and 0.88kg mass is approximately 7J. The energy of balls to grinding the copper ore feed with dimensions less than 1 inch and the Mohs hardness scale 3, is enough [23, 24]. An experiment has been carried out to investigate whether the mill has been well designed in terms of operational parameters such as size and volume of the balls, number, height and face angle of the lifters, speed, etc. or not. Therefore, 20% of the mill volume was filled with the balls. Besides, the slurry concentration is 60% and the slurry filling is U=1. Then, the mill worked for 10 min with 75% of the critical speed.

In Fig. 4, the sizing analysis of the product from the mill grinding mechanism is depicted. As seen in Fig. 4, the mill grinding mechanism is a combination of impact and abrasive breakage mechanisms. If there is just an abrasive mechanism, the materials remain in their initial size or a bit smaller than one, and a huge amount of small particles are produced. However, in the impact mechanism, the amounts of very large and very small particles are small. Obviously from Fig. 4, there is no particle with large or medium size in the mill product while most of the particles are tiny, consequently, it can be stated that the mill grinding mechanism is a combination of both impact and abrasion mechanisms.

In order to assess the influence of ore filling (feed filling) on the wear of lifters in dry milling, the mill is allowed to rotate at 75% of the critical speed and the balls with a mass of 352kg have occupied 20% of the mill volume. According to Fig. 5, the lifters' wear increases with the increase of charge filling ratio in the mill under the dry condition. Because, under the dry condition, the pool is not formed anymore, and with the increase of charge and therefore increase of material mass in the mill, the normal force applied to the lifters augments, consequently the rate of wear rises.

To examine, the influence of U on the wear of lifters, the mill speed was set to 75% of the critical speed and the slurry with 60% of concentration was used. Besides, the balls filled 20% of the mill volume (almost 352kg). In Table 2 and Fig. 6, the variation of wear in terms of slurry filling was depicted. In wet condition, the formed slurry pool in the mill has a profound effect on the absorption of the balls' energy. In other words, with the formation of the slurry pool, the energy due to the impact loads is lowered and the contribution of impact to the wear is reduced.

Apparently from convex Fig. 6, the minimum wear of lifters occurs at U=2, in which with the increase of slurry volume and the pool formation, the wear decreases. It is noted that with the increase of slurry volume, the pool is formed in the mill for $U\geq1$ [5, 25], consequently, the impact loads are

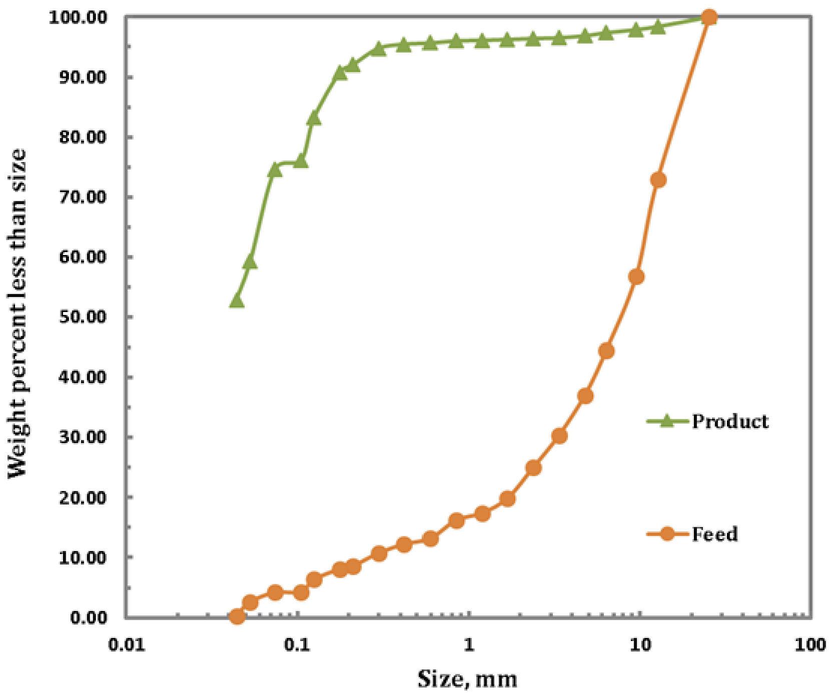

Fig. 4. Size distributions of product from the mill grinding mechanism (Jb=0.2, ΦC=0.75, C=0.6, U=1).

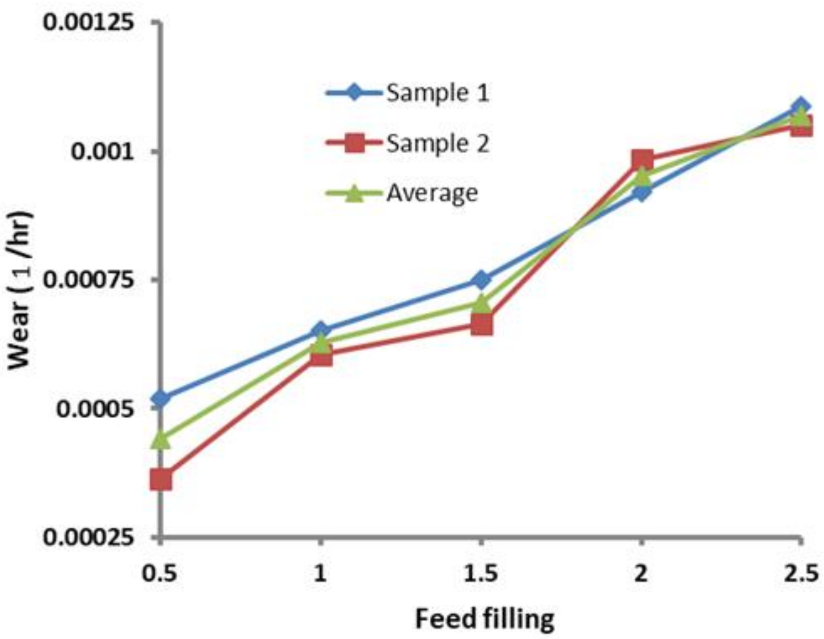

Fig. 5. Wear rate at different ore filling in dry milling (J_b=0.2, Φ_C=0.75).

Table 2. Wear at different slurry filling in wet grinding (J_b=0.2, Φ_C=0.75, C=0.6).

Slurry filling	Ball mass	Slurry mass	Average wear rate
U=0.50	352kg	35kg	0.002072 1/hr
U=1.00	352kg	71kg	0.001719 1/hr
U=1.50	352kg	106kg	0.001557 1/hr
U=2.00	352kg	142kg	0.001397 1/hr
U=2.50	352kg	177kg	0.001429 1/hr

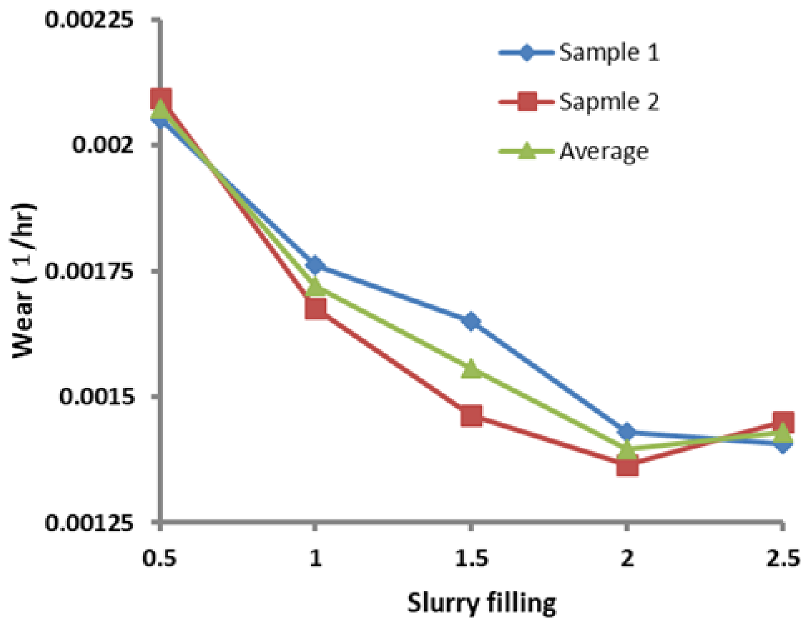

Fig. 6. Wear rate at different slurry filling in wet grinding (J_b=0.2, Φ_C=0.75, C=0.6).

absorbed and damped by the pool. Also, with the decrease of impact loads, the contribution of wear caused by the impact is lowered, and with the constancy of wear because of the abrasion and corrosion, the total wear is reduced. It is important to state that on the one hand, with the increase of slurry volume and the increase of materials weight in the mill, the normal force on the lifters should increase, but on the other hand, with the formation of the pool, the buoyancy (Archimedes) force on the materials is increased in which the resultant normal force is lowered. Therefore, the effects of normal force can be ignored until U=2. Having U between 2 and 2.5, the normal force on the lifters is increased due to the increase of materials weight and conquest of the buoyancy force. Therefore, for 2<U<2.5, the wear rate increases.

Fig. 7 exhibits that with the increase of U from 0.5 to 1.5 and then to 2.5, the values of impact forces reduce. These impact forces were measured using a load cell sensor mounted under one of the lifters for one rotation of the mill. It is noted that the coordination was chosen to be at 12:00 o'clock and all angles were measured based on that point. According to Fig. 7, with the increase of formed pool level and also with the increase of slurry density, the pool acts like a damper in which the impact loads decrease more and consequently the wear of lifters which was caused by the impact is lowered.

The wear of lifters at the different densities of slurry (or slurry concentration) was depicted in Fig. 8. In order to assess the influence of density on the wear, the mill is allowed to rotate at 75% of the critical speed and the balls with the mass of 352kg have occupied 20% of the mill volume. Also, the slurry with 40, 50, 60, 70, and 80% of the solid as a feed charge with the approximate mass of 59, 64, 71, 79, and 88kg was used. In each test, the slurry filling was chosen to be unity (U=1).

In concave Fig 8, wear is shown under various

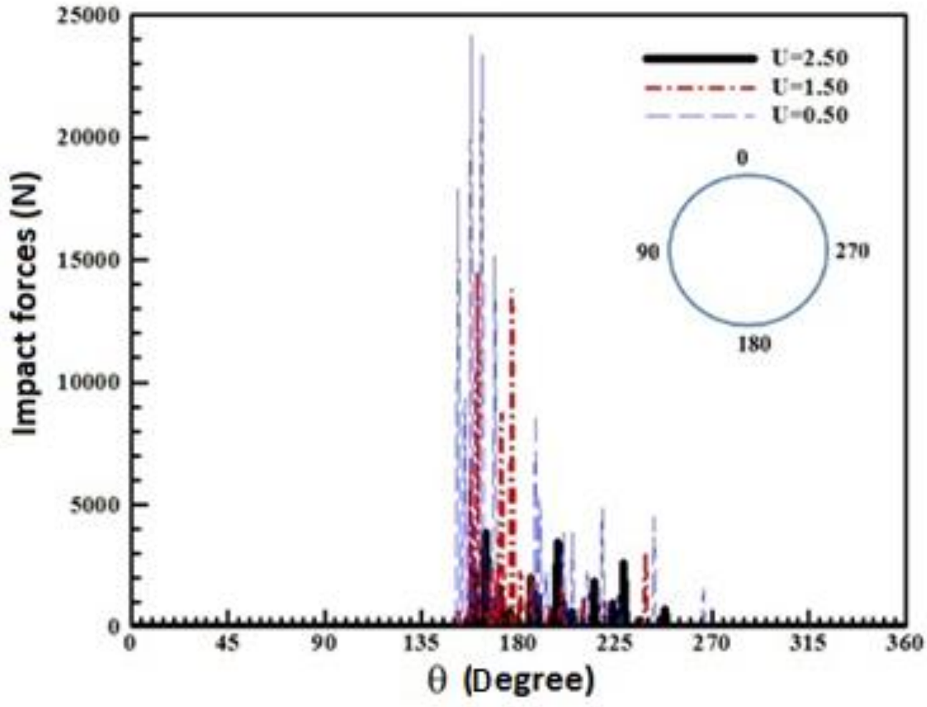

Fig. 7. Impact forces in one rotation of the mill at different slurry filling (J_b=0.2, Φ_C=0.75, C=0.6).

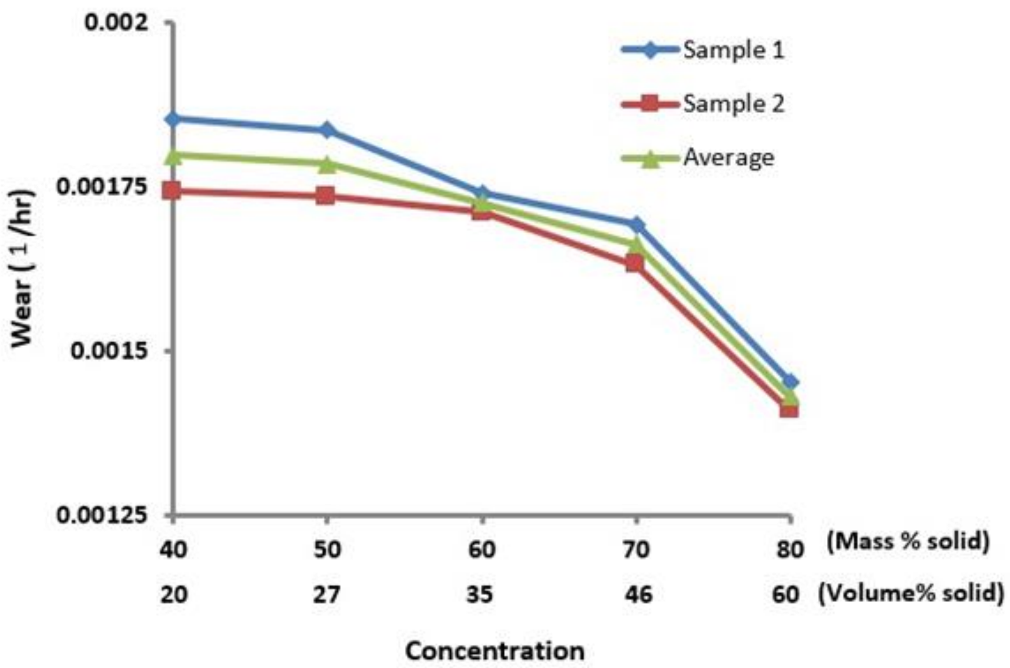

Fig. 8. Wear rate at a different slurry concentration in wet grinding (J_b=0.2, Φ_C=0.75, U=1).

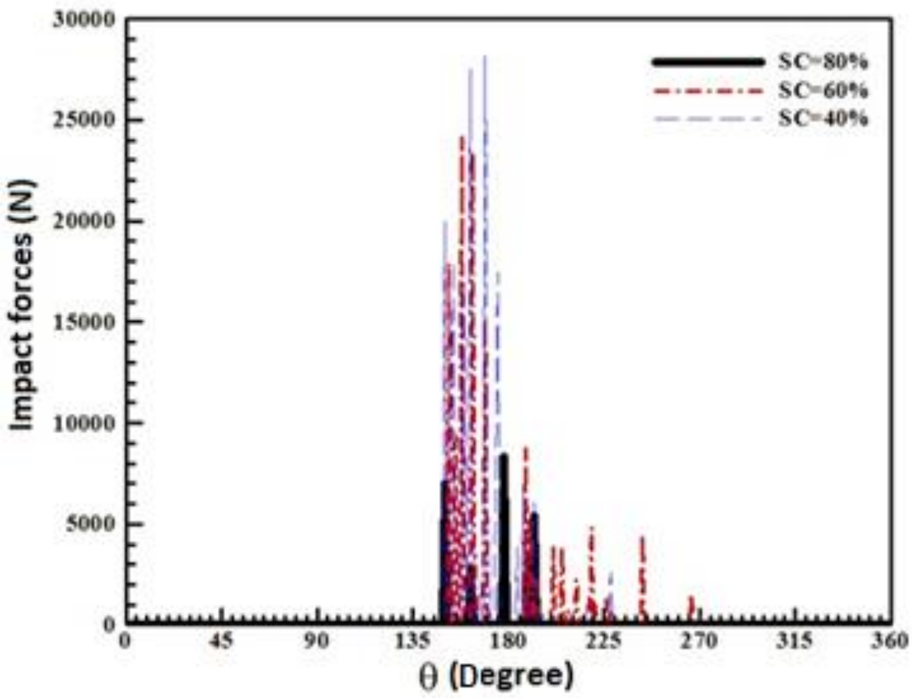

Fig. 9. Impact forces in one rotation of the mill at different concentrations (J_b=0.2, Φ_C=0.75, U=1).

concentrations. Comparison between the results obtained from different densities reveals that the wear of lifters is more at low concentrations due to the low viscosity and density of the slurry and consequently the increase of relative speed between the materials and the lifters. When the slurry density and viscosity are low, the particles move more simply among the balls and cross the lifters at a higher speed, therefore, the abrasion wear improves. On the other hand, at very high density and viscosity, the slurry acts as a damper and creates resistance of the ball's movements to the impact. Consequently, the impact wear improves when there is a reduction of slurry viscosity.

With the formation of the slurry pool and the increase of its density, the energy of impact forces reduces, and thus, the contribution of impact in wear is lowered. With the increase of slurry concentration from 40% to 60% and then to 80%, the values of impact forces are reduced according to Fig. 9. The materials packing between lifters and the walls occur at a concentration of 80%. Due to the packing, the wear of lifters at a concentration of 80% is quite different from other results.

The comparison between dry and wet conditions reveals that the wear rate under the wet condition is significantly more than in the dry condition because of the existence of wear caused by corrosion and also the rise of relative velocity between the materials and the lifters.

Under the wet condition, the material move simply with higher speed among the balls and on the lifters than in the dry mode. With the increase of the slurry density, the relative velocity decreases, and the wear reduces. The column chart in Fig. 10 illustrates the average rate of wear for wet and dry conditions. Fig. 10 is shown for three wet and two dry modes. In wet conditions, with a slurry concentration of 0.4, the wear is equal to 0.001799 1/hr, and with increasing slurry concentration to 0.6, wear decreases and becomes 0.001721. Also, by increasing the slurry filling from 1 to 2, the wear is reduced again and becomes 0.001397. But in the dry condition, the wear behavior of the liner changes in the mill, and as the feed doubles, the wear increases from 0.000629 to 0.000952.

Accordingly, the wear under the wet conditions with different slurry filling and different slurry concentrations is approximately 1.5 to 3 times greater than in the dry condition with different feed filling. The difference between dry and wet wear rates could also be the result of dry fines cladding on the liners and thereby giving them some wear protection. The hardness of materials (lifters, balls, and ores) is very important. Therefore, it should be noted that the difference in the wear rates for wet or dry media is depended on many parameters.

4- Conclusions

In this work, an experimental method was used to investigate the effects of the slurry filling and slurry concentration on the wear of lifters/liners under dry and wet conditions. The following remarks can be drawn from this study:

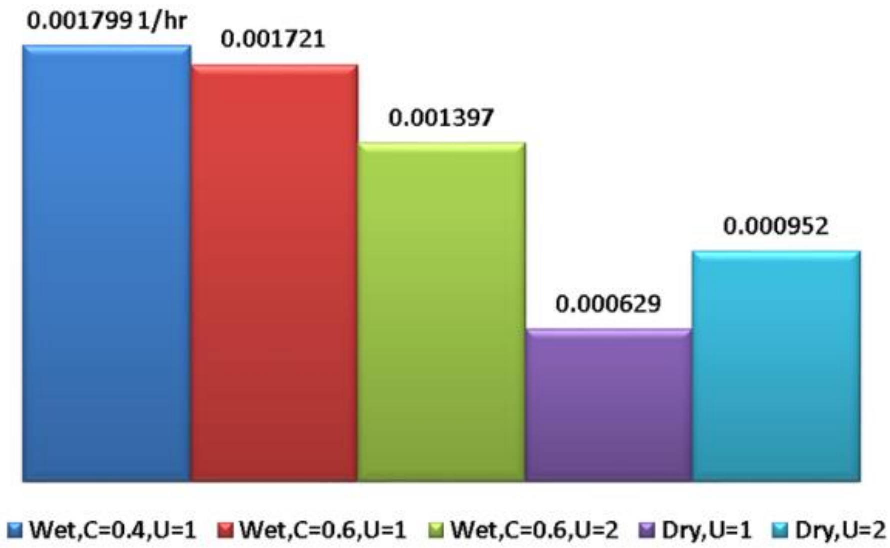

Fig. 10. Wear of lifter in dry and wet milling (J_b=0.2, Φ_C=0.75).

The mill grinding mechanism in this pilot mill is a combination of both impact and abrasion mechanisms.

The lifters' wear increases with the increase of feed filling in the mill under dry condition. Because, under the dry condition, the pool is not formed anymore, and with the increase of charge and therefore increase of material mass in the mill, the normal force applied to the lifters augments, consequently the rate of wear rises.

The minimum wear of lifters was observed when the slurry volume is 2 times the ball bed voidage volume.

The maximum wear occurs at the slurry concentration of 40%. With the increase of the slurry density, the relative velocity decreases, and therefore, the wear is reduced.

With the increase of slurry volume, the pool is formed in the mill. With the increase of formed pool level and also with the increase of slurry concentration and density, the pool acts like a damper in which the impact loads decrease more, consequently, the wear rate is lowered.

The rate of wear in the wet milling is 1.5–3 times greater than in the dry condition. It might be due to changes in slip relative to the lifter surface and the influence of corrosion. In wet grinding, the relative velocity between the materials and the lifters is more than in dry mode.

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References

[1] B. Wills, T. Napier–Munn, Mineral Processing Technology, Elsevier Science & Technology Books, PP108-117, (2006) 267-352.

[2] Y. Ali, C. Garcia-Mendoza, J. Gates, Effects of 'impact'and abrasive particle size on the performance of white cast irons relative to low-alloy steels in laboratory ball mills, Wear, 426 (2019) 83-100.

[3] A. Abbasi, S. Amini, G. Sheikhzadeh, Investigation of the Wear Behavior of Graphite Steel (GSH48) in Ultrasonic Peening Process, Amirkabir Journal of Mechanical Engineering, 50(3) (2018) 529-540.

[4] P. Fazio, Annual Book of ASTM Standards, Wear and Erosion; Metal Corrosion, ASTM G102-89. Standard Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements, ASTM, Philadelphia, (2004).

[5] M. Soleymani, M. Fooladi Mahani, M. Rezaeizadeh, Experimental study the impact forces of tumbling mills, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 231(2) (2017) 283-293.

[6] P. Radziszewski, S. Tarasiewicz, Modelling and simulation of ball mill wear, Wear, 160(2) (1993) 309-316.

[7] P. Radziszewski, S. Tarasiewicz, Simulation of ball charge and liner wear, Wear, 169(1) (1993) 77-85.

[8] P.W. Cleary, Predicting charge motion, power draw, segregation and wear in ball mills using discrete element methods, Minerals Engineering, 11(11) (1998) 1061-1080.

[9] J. Kalala, M. Bwalya, M. Moys, Discrete element method (DEM) modelling of evolving mill liner profiles due to wear. Part II. Industrial case study, Minerals Engineering, 18(15) (2005) 1392-1397.

[10] S. Banisi, M. Hadizadeh, 3-D liner wear profile measurement and analysis in industrial SAG mills, Minerals Engineering, 20(2) (2007) 132-139.

[11] M. Yahyaei, S. Banisi, Spreadsheet-based modeling of liner wear impact on charge motion in tumbling mills, Minerals Engineering, 23(15) (2010) 1213-1219.

[12] M. Rezaeizadeh, M. Fooladi, M. Powell, S. Mansouri, N. Weerasekara, A new predictive model of lifter bar wear in mills, Minerals Engineering, 23(15) (2010) 1174-1181.

[13] M. Rezaeizadeh, M. Fooladi, M. Powell, N. Weerasekara, An experimental investigation of the effects of operating parameters on the wear of lifters in tumbling mills, Minerals Engineering, 23(7) (2010) 558-562.

[14] P. Radziszewski, Ball charge dynamics and liner wear simulation, in: Canadian Mineral Processors Conference, 1997.

[15] P. Radziszewski, R. Varadi, T. Chenje, L. Santella, A. Sciannamblo, Tumbling mill steel media abrasion wear test development, Minerals Engineering, 18(3) (2005) 333-341.

[16] R. Hebbar, Investigation on grinding wear behaviour of austempered ductile iron as media material during comminution of iron ore in ball mills, Transactions of the Indian Institute of Metals, 64(3) (2011) 265-269.

[17] M.M. Mourad, S. El-Hadad, M.M. Ibrahim, Effects of molybdenum addition on the microstructure and mechanical properties of ni-hard white cast iron, Transactions of the Indian Institute of Metals, 68(5) (2015) 715-722.

[18] H. Hatami, A. Fathollahi, Theoretical and numerical study and comparison of the inertia effects on the collapse behavior of expanded metal tube absorber with single and double cell under impact loading, AUT J Mech Eng, 50 (2018) 999-1014.

[19] H. Hatami, M. Shariati, Numerical and experimental investigation of SS304L cylindrical shell with cutout under uniaxial cyclic loading, Iranian Journal of Science and Technology, Transactions of Mechanical Engineering, 43(2) (2019) 139-153.

[20] A.G. Jahromi, H. Hatami, Numerical behavior study of expanded metal tube absorbers and effect of cross section size and multi-layer under low axial velocity impact loading, AUT J Mech Eng, 49 (2018) 685-696.

[21] M. Mohammadi Soleymani, M. Fooladi Mahani, M. Rezaeizadeh, M. Bahiraie, Experimental study of mill speed, charge filling, slurry concentration, and slurry filling on the wear of lifters in tumbling mills, Modares Mechanical Engineering, 15(4) (2015) 265-271.

[22] L. Austin, R. Klimpel, P. Luckie, Process engineering of size reduction: ball milling, Soc, Min. Eng. AIME, New York, NY, (1984) 112-113.

[23] M. Akhondizadeh, M. Rezaeizadeh, Effect of specimen size and ball size on breakage throughput in the drop-weight test, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 233(2) (2019) 202-210.

[24] M. Razani, A. Masoumi, M. Rezaeizadeh, M. Noaparast, Prediction model to estimate the specific energy and product particle size distribution of semi-autogenous mill, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 233(2) (2019) 306-313.

[25] M. Soleymani, M. Fooladi, M. Rezaeizadeh, Effect of slurry pool formation on the load orientation, power draw, and impact force in tumbling mills, Powder Technology, 287 (2016) 160-168.

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