

# 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 of 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 20% and mill speeds 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 condition. During 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 dry mode and the wear is 1.5–3 times greater than the dry condition.

Keywords: Tumbling mill, Wear of the liner, Slurry, Dry condition, Wet condition.

## 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 due to impact and abrasion processes. For wear protection, the inner surface of the mill is covered by liner. Mills work in the two forms of dry and wet. The wear of liners affects

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the mill performance because of the loss of lifting. In addition, the substitution of worn lifters takes substantial amount of time and energy of technicians. Besides, unsystematic breakage and the lifters replacement would cause several undesirable downtime 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 in the following five types: adhesive wear, abrasive wear, surface fatigue, fretting wear and erosive wear [3, 4]. Additionally, it ought to be noticed that the corrosion happens especially in the wet grinding. Fig.1 [5] shows the load behavior in a wet 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 have explained how the DEM could be used for the wear prediction [8]. 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 has proposed an equation for mass loss in a tumbling mill [14, 15].

The previous results showed that nothing happened within a laboratory ball mill and this has the right to be depicted as an effect impact in 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, can refer to the research of Hatami et al. [18-20]. But less research has been done on impact wear. It is important to note that a few studies have been published to assess the wear of lifters in tumbling mills under the 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.

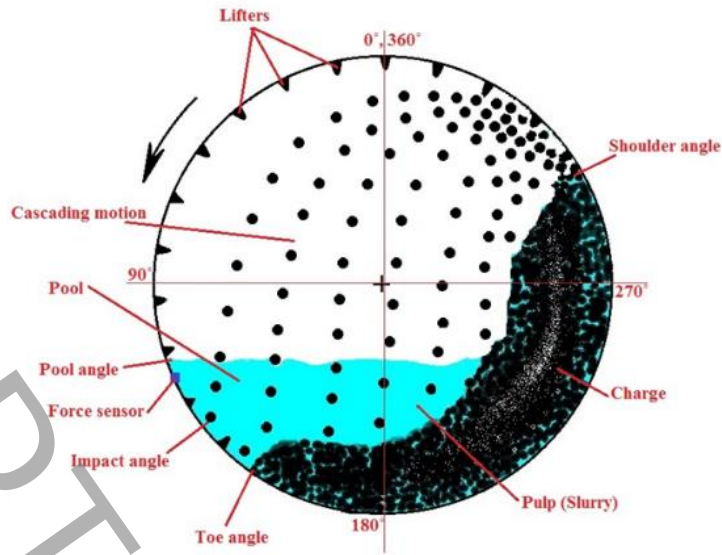


Fig. 1. Definition of the load behavior in a wet tumbling mill [5].

## 2. Experimental method

Experimental pilot mill is showed in Fig. 2. There are 15 lifters with 50mm height and face angle of  $30^\circ$ . 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, 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 the 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 of the balls bed voidage. The concept of slurry filling in the mills was first introduced by Austin et al. [22].



Fig. 2. Pilot mill.

In order to investigate the wear, the wear specimens are installed in two of the lifters. These lifters have 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 the 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 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 weighted 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.



Fig. 3. Specimens and holder lifters of specimens.

Table 1. Mill characteristics and grinding conditions.

|                |                                         |                                                                                                 |
|----------------|-----------------------------------------|-------------------------------------------------------------------------------------------------|
| Mill           | diameter                                | 1000 mm                                                                                         |
|                | length                                  | 500 mm                                                                                          |
|                | speed                                   | 31 rpm                                                                                          |
|                | fraction of critical speed ( $\Phi_c$ ) | 0.75                                                                                            |
|                | Lifters                                 |                                                                                                 |
| 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 <sup>3</sup>                                                                          |
|                | ball filling ( $J_b$ )                  | 0.2 fraction of mill volume                                                                     |
|                | total ball mass                         | 352 kg                                                                                          |
| Feed           |                                         |                                                                                                 |

|                          |                                                                           |
|--------------------------|---------------------------------------------------------------------------|
| material                 | copper ore                                                                |
| particle size            | $F_{100} = 25.4$ , $F_{80} = 12.7$ , $F_{50} = 8$<br>and $F_{10} = 0.3mm$ |
| ore density              | 2700 kg/m <sup>3</sup>                                                    |
| 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 <sup>3</sup>                        |
| slurry filling (U)       | $U=0.5 - 2.5$ (as volume fraction of ball bed voidage)                    |

The results of 15 different experiments which assessed the effects of the mill condition in 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 the 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  $\pm 0.00002$  1/hr at 98% confidence level.

### 3. Results and Discussion

In a pilot mill with 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]. On 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 from the 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 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.

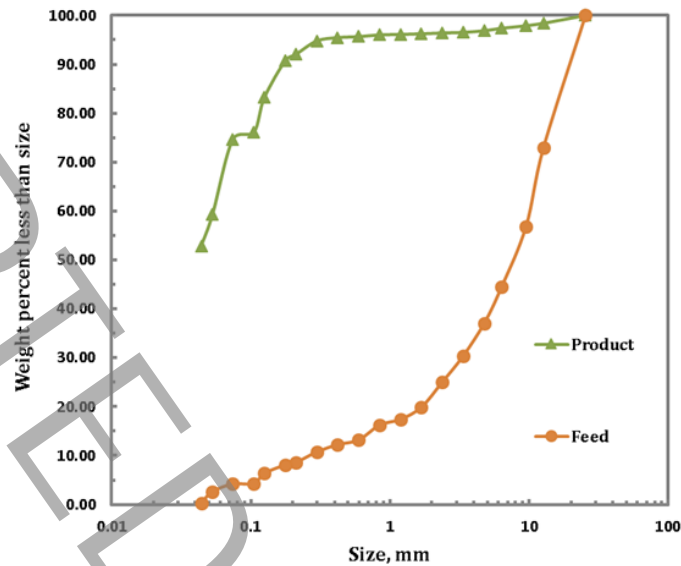


Fig. 4. Size distributions of product from the mill grinding mechanism ( $J_b=0.2$ ,  $\Phi_c=0.75$ ,  $C=0.6$ ,  $U=1$ ).

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 with 75% of the critical speed and the balls with the 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.

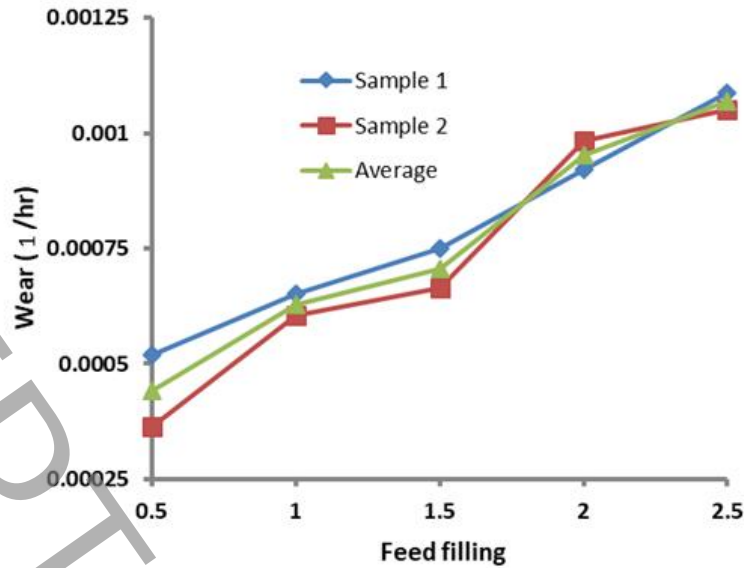


Fig. 5. Wear rate at different ore filling in dry milling ( $J_b=0.2$ ,  $\Phi_c=0.75$ ).

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  $U \geq 1$  [5, 25], consequently, the impact loads are 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 the buoyancy force. Therefore, for  $2 < U < 2.5$ , the wear rate increases.



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

| 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     |

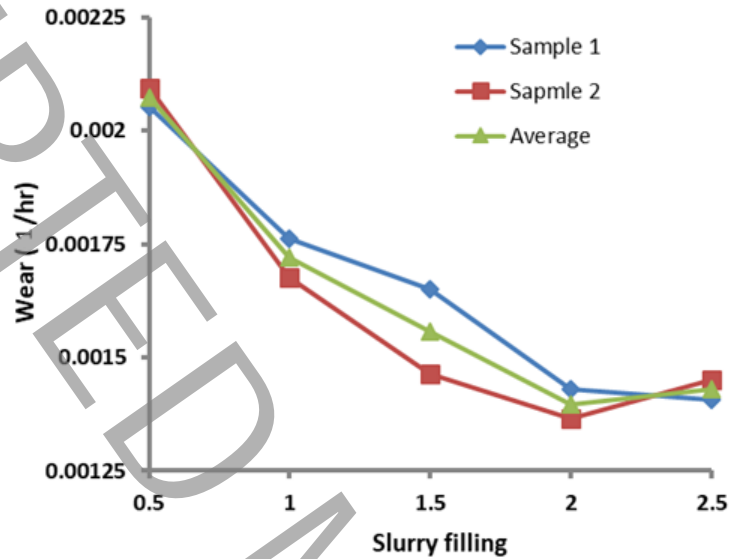


Fig. 6. Wear rate at different slurry filling in wet grinding ( $J_b=0.2$ ,  $\Phi_C=0.75$ ,  $C=0.6$ ).

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.

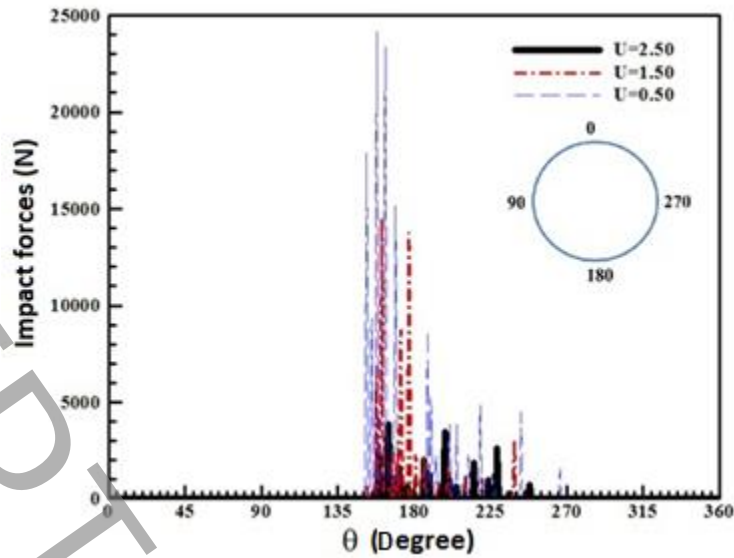


Fig. 7. Impact forces in one rotation of the mill at different slurry filling ( $J_b=0.2$ ,  $\Phi_C=0.75$ ,  $C=0.6$ ).

The wear of lifters at the different density 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 with 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 approximate mass of 59, 64, 71, 79 and 88kg was used. In each tests, the slurry filling was chosen to be unity ( $U=1$ ).

In concave Fig 8, wear is shown under various concentrations. Comparison between the results obtained from different density reveals that the wear of lifters is more at low concentration 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 with 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 movements to the impact. Consequently, the impact wear improves when there is a reduction of slurry viscosity.

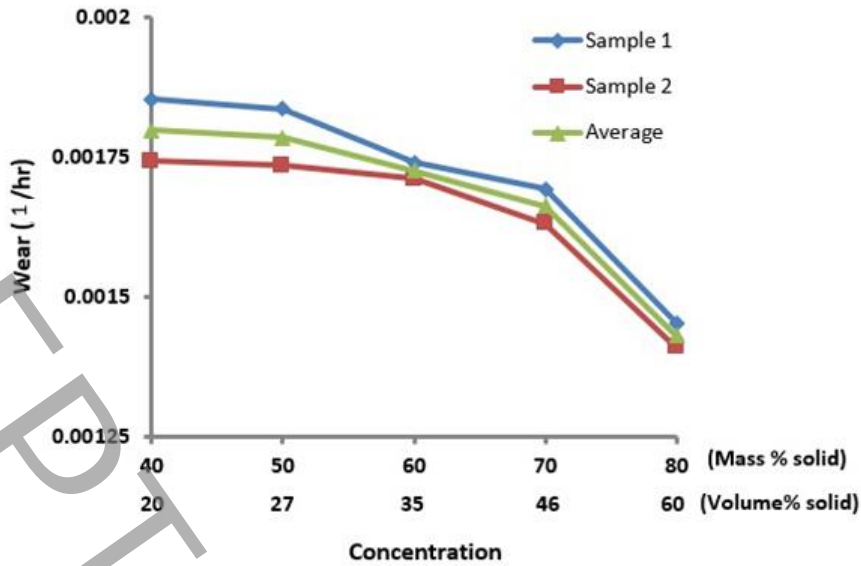


Fig. 8. Wear rate at different slurry concentration in wet grinding ( $J_b=0.2$ ,  $\Phi_C=0.75$ ,  $U=1$ ).

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 concentration of 80%. Due to the packing, the wear of lifters at concentration 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 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.

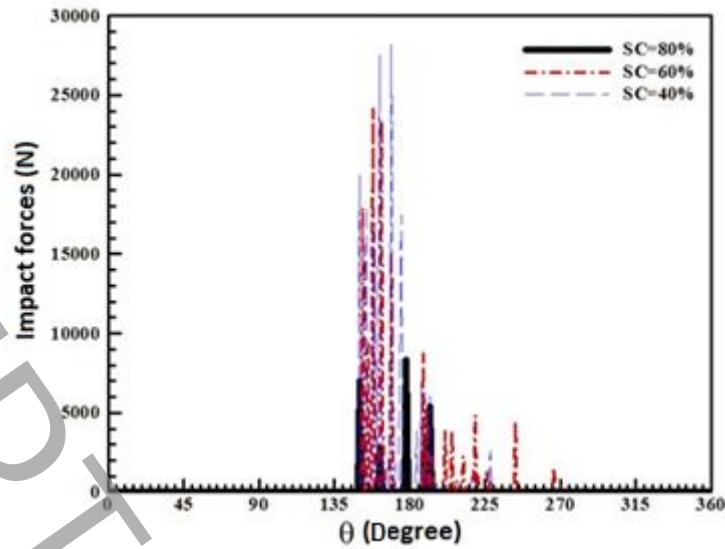


Fig. 9. Impact forces in one rotation of the mill at different concentration ( $J_b=0.2$ ,  $\Phi_C=0.75$ ,  $U=1$ ).

Under the wet condition, the material move simply with higher speed among the balls and on the lifters than the dry mode. With the increase of the slurry density, the relative velocity decreases, and the wear reduces. The column chart of Fig. 10 illustrates the average rate of wear for wet and dry condition. 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.

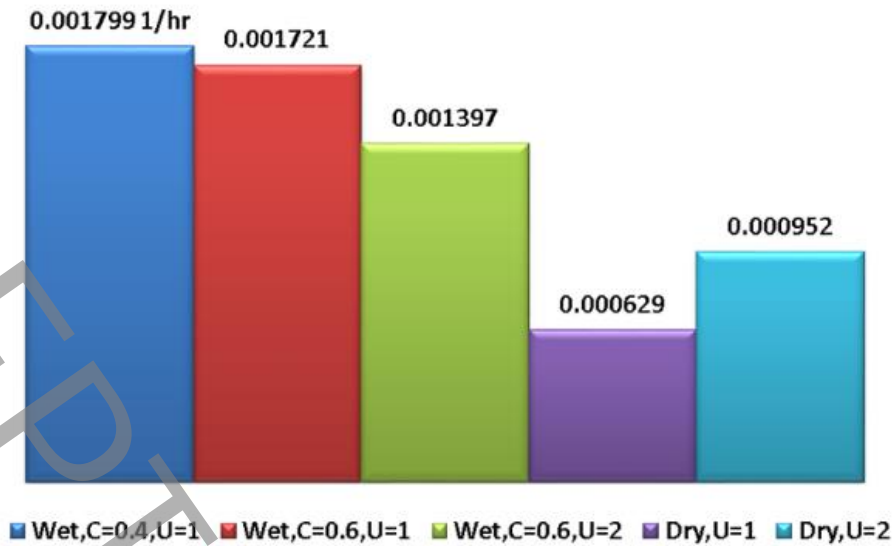


Fig. 10. Wear of lifter in dry and wet milling ( $J_b=0.2$ ,  $\Phi_C=0.75$ ).

Accordingly, the wear under the wet conditions with different slurry filling and different slurry concentration is approximately 1.5 to 3 times than 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) are very important. Therefore, it should be noted that the difference of the wear rates for wet or dry media are depended to 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:

- 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 of 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 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 dry mode.

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