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Effect of slurry pool formation on the load orientation, power draw, and impact force in tumbling mills

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ABSTRACT

The present paper aims to investigate: 1) the impact forces in terms of variables like: mill speed, slurry concentration, and slurry filling; 2) the key points of load orientation, namely the shoulder, toe, impact, and pool angle in wet grinding; and 3) the influences of the slurry pool formation on the mill power draw. In this work the influence of these operating parameters were investigated using a pilot mill (1000 ∗ 500 mm). To this end, a Copper ore (−1000 μm) was used to prepare slurry at 50% solid concentration by mass. The tests covered a range of slurry filling (U) from 0 to 2.5 with ball filling 30% of mill volume and 6 different speeds between 60% and 85% of critical speed. It is observed as the mill speed increases, the shoulder angle will increase and the impact angle will decrease. By formation of the pool and exertion of the floating (buoyancy) forces to the particles inside the mill, the toe angle increases 15–25°. The results delineate that the increase in the mill speed leads to a remarkable increase in the magnitude and frequency of the impact forces. An increase in slurry filling and the resulting formation of the pool, the impact forces will decrease. It is found that with the increase in slurry concentration, the slurry will act as a damper decreasing the impact forces. Results show that there are a definite trend between the power draw and the slurry filling.

1 . Introduction

Mills are difficult to investigate because they are complicated dynamic systems and dependent on multiple factors. They are generally stopped for maintenance purposes only [1]. In such complicated systems, some attempts have been conducted with the aim of predicting and simulating the mills.

Mills work in the two forms of dry and wet conditions (grate discharge and overflow discharge). In wet grinding, however, depending on the ore that has to be fractured, water is used in the mill as a factor to remove the grinded stones from the mill in the form of slurry. This method has some disadvantages, including the corrosion role of water against metals and its damping role against the impact forces inside the mill which leads to the decrease in mill efficiency [2,3]. By the slurry pool formed inside the mill, impact forces, the load behavior and mill power draw change.

Maleki-Moghaddam et al. [4], Yahyaei and Banisi [5] have developed an application in Microsoft Excel (called “GMT”), using Powell's analytic relations [6] with the aim to simulate the path for material movements inside the mill. The dynamic behavior of the load in wet condition has been studied in industrial as well as pilot scale [7,8]. Katubilwa and Moys [9] have conducted some experiments by different viscosity in 60% of the critical speed by means of a pilot mill (552 mm diameter, 180 mm length, 18 lifters of 25 mm height and 20̊ angle, 20% charge of ball with 10 mm diameter); they made a fluid by combination of water and glycerin oil to different densities 1000–1202 kg/m^3 (this density range are not applied in mineral industries) and then studied the effect of the slurry filling and viscosity inside the mill on the shoulder, toe, and pool angles. But in this article the real slurry (pulp) was used. Shi and Napier-Munn [10] have studied the effect of slurry viscosity on grinding. Cleary and Morrison [11,12] have analyzed the experimental mill of 1.8 m diameter, 60 cm length in 3D mode by DEM-SPH method in wet condition.

Forces exerted on the liners/lifters by the cascading motion in tumbling mills (wet and dry) was measured by Moys, et al. [13,14]. It was shown that the increase in the mill speed leads to an increase in the amount of the impact forces and by increasing the load volume leads to decrease the impact forces. Djordjevic, et al. [15,16] have studied the effect of the lifters' height and the mill's speed on the normal impact forces in a mill of 5 m diameter. They concluded that the number of the lifters and their heights, the speed of the mill, and the fill level of the mill

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are very effective on impact forces. Rezaeizadeh, et al. [17,18] have studied the effect of a mill's operational parameter on the impact forces and power draw in dry mills by experimental results; using a pilot mill. In their research, it is shown that the increase in speed will lead to the movement of the load shoulder upward, thus increasing the impact forces. Ebrahimi-Nejad and Fooladi [19] have studied analytically the motion of steel balls in SAG mill; it was shown that as the lifter height or the coefficient of friction increases, the impact position tends to move upward, but the maximum impact force caused by cascade motion in a dry mill of 10 m diameter, decreases.

Effects of operational parameters on the motion of grinding media and power in milling were investigated [20–24]. Moys [25] proposed a model for mill power to describe the effect of mill speed, load volume and liner design on mill power. In 1993 Morrell proposed a theoretical mill power model capable of accounting for the effects of slurry pool. The model set the benchmark in power modeling with its accuracy and applicability to autogenous, semi-autogenous and ball mills. It has been widely observed that the power draw of overflow mills is lower compared to that of grate mills under similar mill geometry and milling conditions [26]. The rheological properties of slurry are determined primarily by the viscosity of the liquid medium and the volume fraction of solid in the slurry, with a less noticeable effect of the particle size distribution was investigated by Tangsathitkulchai, [27,28]. Mulenga and Moys, [29] used pilot mill ($552 * 400$ mm), loaded with 10 mm balls at 20% volumetric filling, was run at 5 different speeds between 65% and 85% of critical. The net power draw and media charge position were measured. After this, the slurried ore was gradually added to the media charge for slurry filling U between 0 and 3. It was found that Morrell's model could not fully explain the effect of slurry volume on net power draw especially for an under-filled media charge ($U < 1$). A piece-wise function was curve-fitted to the power data.

In this work, the effect of the operating parameters of mill, slurry filling, slurry concentration, and mill speed on the power draw, load orientation, and impact forces were experimentally investigated using a pilot mill. The present work provides further insight on the slurry pooling phenomenon. It should be noted that Katubilwa and Moys [9,29] investigated the load behavior and power draw in wet condition using a small pilot mill. Some of scientific advancements of this work are pointed out here: The data has the potential to elucidate the slurry pooling phenomenon in a way different from any other previous research and using a larger pilot mill (1 m × 0.5 m). A quartz load cell (ergometer) is installed on the mill shell in order to measure impact forces and impact angles alongside other parameters during the slurry pool formation. The novelty of this work is in investigating the impact forces and impact angles. Also, the influences of the slurry pool formation on the mill power draw are investigated.

2 . Experimental

2.1 . Pilot Mill

A pilot mill (1000 mm diameter and 500 mm length) was used for experimentation. The front of the mill is transparent and made of Perspex material. A section of the machine is displayed in Fig. 1. There were 60 lifters of 14 mm height and 14.5° face angle. This pilot mill was capable of using different-size balls; however, just the 25 mm ones were used in this study as the solid load; a grinding media with 30% charge were applied. The mill motor was capable of changing the rotation permanently up to 100% of the critical speed. The conditions of implementing the experiments are shown in Table 1.

This experiment was partly based on taking videos and photos from the contents of a pilot mill to investigate the load orientation. A scaled plate was placed on the fixed frame of the mill so as to observe the key-point angles of the load orientation after taking each photo. Two 500 W projectors were used for providing more light inside the mill thereby producing photographs of good quality. In every experimental condition, the mill was allowed to work for several rotations and then the videos and photos were taken to measure the key point of load. A high-speed camera (CASIO-EX-F1) was used to take photos and films from the mill contents with 60–1200 fps. In each experiment, the load-orientation photos were taken within 5 s by a high-speed camera (60 fps). From among the 300 photos taken, the load orientation including the shoulder angle, toe angle, pool angle, and impact angle (point of impact) were extracted as shown in Fig. 2. The 12:00 o'clock was set as the zero point of the device and all angles were measured accordingly. In order to prevent the Perspex plate wetting by slurry, a Nano material with hydro-phobic properties was sprayed on the Perspex plate.

For investigation of the impact forces in the load, a quartz force sensor mounted through the mill lifter walls was employed to measure the impact load on the lifter. The load cell is mounted on the liner plate; a metal plate of 6 × 22 × 450 mm was used on the load cell with the aim to measure the hits more precisely. The output signal from the quartz sensor was calibrated to known impact forces. Quartz piezoelectric force sensors produce a charge output as a result miniscule stresses on a crystal lattice as opposed to deflection associated with a bonded foil strain gage. Quartz piezoelectric force sensors have the stiffness required to measure high-impact forces with very high frequency. The impact sensor has a threshold sensitivity of 48.8 N. The sensor detects the forces normal to its surface, so when mounted on the shell the impact forces measurements are in the radial direction. Once below the toe of the load the sensor is detecting forces transmitted via the balls in direct contact with it. According to Fig. 3, the impact angle, impact frequency, and impact force magnitude could be calculated using impact load signal which was measured by the quartz load cell. It was possible to measure the angular positions of the media charge that hit to the toe

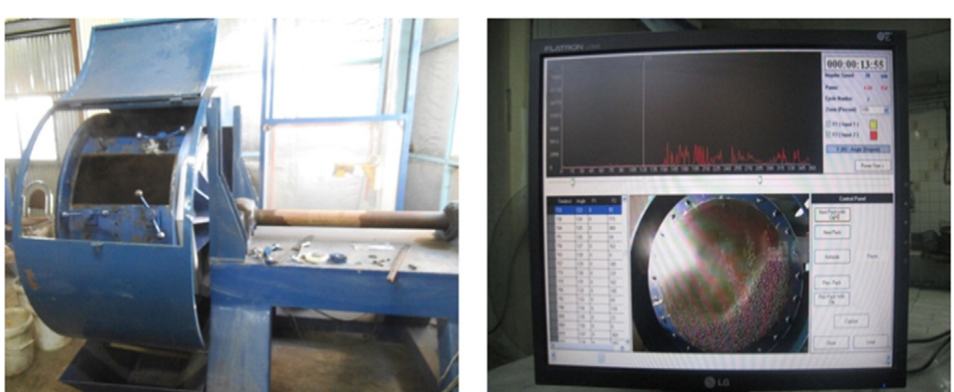

Fig. 1. Schematic of the experimental pilot mill and the monitoring of the device.