Journal of Mineral Resources Engineering, 9(2): 81-91, (2024)

Imam Khomeini International University
Vol. 9, No. 2, Summer 2024, pp. 81-91

نشریه مهندسی منابع معدنی
Journal of Mineral Resources Engineering
(JMRE)

Research Paper

Effect of Grinding Media Shape on Dry Rod Mill Power Draw

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Received: 28 Sep. 2022 **Accepted: 08 Nov. 2022**

Abstract: One of the inseparable components of the grinding process in tumbling mills is the grinding media used in them. Despite the simplicity of grinding media shapes in a tumbling mill, their effect on breakage performance as well as on the mill power draw has remained a complex problem. A large share of energy consumption in mineral processing plants is related to grinding operations, so the study of power consumption in this sector is very important. This study compares the effects of conventional rods (simple rods) and grooved rods on the mill power draw in a dry rod mill at various mill speeds and grinding media filling. The results of the study showed that with an increase in grinding media weight and mill speed, power consumption was increased for both types of grinding media studied. The specific power rate decreased with increasing the speed and media filling. By increasing mill speed, the sensitivity of the specific power draw to the grinding media filling was increased. The specific power draw of grooved rods at low and medium speeds was shown to be more than that of simple rods, but at speeds above 60% of the critical speed, the specific power draw of the grooved rods was lower than that of the simple rods. Using an empirical model, the experimental and model values were compared. The results showed that the prediction of the mill power draw using the presented empirical model, in the range of low and medium speeds is more reliable. Therefore, using this model at low speeds is perfectly valid. However, as speed increases, its credibility decreases.

Keywords: Rod mill, Power draw, Grinding media shape.

How to cite this article
Khani Khereshki, M., Karamoozian, M., and Yahyaei, M. (2024). *"Effect of grinding media shape on dry rod mill power draw"*. Journal of Mineral Resources Engineering, 9(2): 81-91.
DOI: 10.30479/JMRE.2022.17908.1606

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1- INTRODUCTION

Approximately 6% of the total global energy consumed is consumed by comminution processes [1-3]. Only a small fraction of energy is used merely on grinding of minerals in the tumbling mills [4]; Hence, the evaluation of the mill power draw and energy consumption as a key parameter is inevitable.

When selecting comminution devices or any comminution operation, the power required to produce the favorable breakage must firstly be determined [5]. The significance of this issue can be seen in the triple laws of Rittinger (1867), Kick (1883), and Bond (1952) [6]. These laws are described very much in the minerals processing books and papers.

In general, the power draw of mills depends on a number of design variables including mill diameter [5], liner design [7,8], grinding media size and shape [9-11] and the ratio of media to mill diameter [12]. Operational variables such as mill rotational speed, fractional grinding media filling and powder filling percentage [7,12] must also be considered.

Grinding media plays an important role in milling process and finally in downstream processes and pre-treatment of mineral processing [13-17]. Especially, this important effect shows itself during a milling process when the grinding media shape changes due to factors such as impact, abrasion, corrosion and chipping [18]. Important researches have been conducted on the effect of grinding media shape on grinding kinetics, load behavior, power consumption and flotation process, including Cylpebs, Millpebs, Powerpebs, Minipebs [19], Eclipsoids, cubes, as well as a combination of different shapes of grinding media [20], ball with a concave surface [21], various type of cylinders (short, long and Equi-cylinders) with different cross sections such as circular, hexagonal, etc. [22,23], worn balls vs new balls [11], Cylpebs versus balls [24]. It is clear that grinding media shape as a design variable can have an effect on the power draw, and by changing the shape of grinding media, the milling performance can be affected due to the difference in contact mechanisms and variations in the media's mass and surface area [10]. These mechanisms can be investigated from two different viewpoints:

1: Contact between grinding media, media with mill liners and finally their effect on the mill power draw.

2: Contact between mineral particles and media and their aspect of particles breakage kinetics.

Regarding the design and operational variables such as the grinding media shape, the mill speed and the fractional mill filling by media, investigating the mill power draw as a key parameter for controlling the grinding process is very important [25].

To date, only a few studies have investigated the effect of grinding media shape on the mill power draw in the ball mill [25,26]. The effect of various shapes of grinding media (balls, worn balls and Cylpebs) on the power draw and the moving behavior of the media in the ball mill has been investigated by Lameck et al. [25]. Although a few fundamental studies on the effect of the grinding media shape were conducted for ball mills or between ball and rod in tumbling mills, but rod shapes in rod mills has not received the same level of attention [27]. Despite a lot of changes and manufacture of new grinding equipment (AG/SAG mills, HPGRs and …), rod mills are still the best option for grinding some minerals. This is due to their ability to produce uniformly sized and high-quality products, as well as the reduction of slime [28-30].

It is assumed that grooved rods can decrease power draw due to a decrease in the contact surface of the grinding media with the liner. On the other hand, the weight loss of grooved rods compared to the same size distribution of simple rods can reduce the mill power draw. Also, the purpose of choosing this shape was based on the assumption that creating groove along of rod will cause better trapping of mineral particles between the grinding media and increasing the particles breakage kinetics; like what happens in toothed roller crushers. Due to the studies and experimental equations presented by other researchers [5], which are also discussed in the following and in which only the power draw in each ton of grinding media is considered, in this study, the authors try to investigate the effect of grinding media shapes on the power draw. The purpose of this study is to investigate and analyse the complexity of some parameters in the milling operation and not to introduce a new grinding media as an alternative to simple grinding media in a rod mill. It should be noted that in this study, only viewpoint number 1 for measurement of the power draw has been examined. Generally, this study investigates the effects of grinding media shapes on the power draw of the dry rod mill as a function of mill speed and the fractional mill filling by media.

2- EXPERIMENTS

2-1- Laboratory mill setup

The power draw experiments were conducted in a batch laboratory scale rod mill equipped with a variable speed motor and a torque meter in order to measure torque. The internal diameter and length of the mill were 7 ft. (177.8 mm) and 14 ft. (355.6 mm), respectively. The mill had six trapezoidal type liners with angle and base widths of 30˚ and 1 cm, respectively.

2-2- Grinding media

For these experiments, two grinding media (simple and grooved rods) were used. Simple rods are the conventional grinding media used in rod mills. Each grooved rod had a cross section that looked like a symmetrical 6-petal flower at each point across the length of the rod and these grooves were extended along the rod. The depth of each groove was 15 percent of the rod diameter. This shape was selected in order to have the least impact on the rolling of grinding media, while providing space for particles to be captured inside the grooves. The length of the rod for each shape was 34 cm and the rods' diameters were 25, 20 and 15 mm, respectively. The shapes of the simple rods and grooved rods used in the power draw experiments are shown in Figure 1.

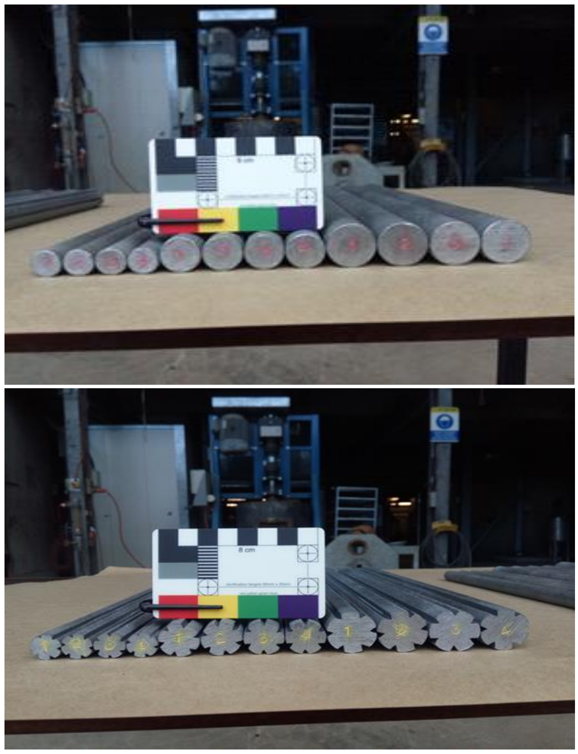

Figure 1. Simple and grooved rods

2-2-1- Test procedure

The power draw at different mill speeds and grinding media filling was measured in the study tests. The mill speed values were at 40 (low speed), 60 (medium speed) and 80 (high speed) percent of the critical speed. To investigate the effect of the fractional mill filling by media (J_r) on the power draw, three fractional rod fillings (15.5%, 18.5% and 25%) were evaluated. Equation 1 was used to calculate the fractional rod filling [31].

$$\text{Charge volume (rod filling } J_r\%) = 113.7-127.3\,(H_C/D_M),\ H_C>0,\ H_C/D_M<0.893 \quad (1)$$

Where:

D_M and H_C: are the internal diameter of the mill and the distance between grinding media level and top of the mill, respectively.

Based on the Equation 1, in order to achieve 25%, 18.5% and 15.5% of the fractional mill filling by media, 12, 9, and 6 rods were needed, respectively, which were equally distributed between the three different rod diameters. The experimental conditions and the weights of grinding media in each of the fractional mill filling by media are presented in Table 1 and Table 2, respectively.

2-2-2- Power draw

The mill power draw equation by Hogg [32] is presented in Equation 2.

$$P=2\pi N\tau/60 \quad (2)$$

Where:

P: power draw in kWh

N: the mill speed in RPM

τ: is the torque applied by the mill minus friction in the bearings in Nm.

In this study, the power draws of two grinding media were calculated after measuring the torque by a torque meter using Equation 2. In order to prevent device errors, the calibration of the torque meter was checked at specific times in all stages of the experiments.

Rowlands and Kjos presented another equation for determining the rod mill's power draw (Equation 3) [5].

$$P=1.752D^{0.33}(6.3-5.4V_p)\varphi_c \quad (3)$$

Where:

P: rod mill's power drawn per mass of rods in kWh/tone

D: the internal mill diameter in meter

V_p: is the fractional of rods filling

φ_c: is the mill speed in the percentage of critical mill speed.

This equation was used to validate the values

Table 1. The experiments conditions

Parameters	Grinding media	
	Simple rods	Grooved rods
Media diameter size (mm)×No.	25×4, 20×4, 15×4 25×3, 20×3, 15×3 25×2, 20×2, 15×2	25×4, 20×4, 15×4 25×3, 20×3, 15×3 25×2, 20×2, 15×2
Mill diameter (ft. - mm)	(7 - 177.8)	(7 - 177.8)
Mill length (ft, mm)	(14 - 355.6)	(14 - 355.6)
Mill volume (cm^3)	8530	8530
Critical speed, N_c, (RPM)	108	108
Mill speed (Critical speed %)	40 (low speed), 60 (mediumspeed) 80 (high speed)	40 (low speed), 60 (medium speed) 80 (high speed)
Lifters type×No.	Trapezoidal×6	Trapezoidal×6
Fractional mill filling by media, J_r (%)	25, 18.5, 15.5	25, 18.5, 15.5

Table 2. The weights of grinding media

Fractional mill filling by media (%)	Grinding media					
	Simple rods			Grooved rods		
	Dimension (mm) (length×diameter)	Number	Total weight (gr)	Dimension (mm) (length×diameter)	Number	Total weight (gr)
25 %	340*25	4	5228.8	340*25	4	4674.7
	340*20	4	3354.5	340*20	4	2978.1
	340*15	4	1872.6	340*15	4	1669.3
	Total	12	10455.9	Total	12	9322.1
18.5%	340*25	3	3921.7	340*25	3	3506.9
	340*20	3	2515.7	340*20	3	2233.1
	340*15	3	1404.5	340*15	3	1251.4
	Total	9	7841.9	Total	9	6991.4
15.5%	340*25	2	2614.4	340*25	2	2337.9
	340*20	2	1677.7	340*20	2	1488.3
	340*15	2	936.6	340*15	2	834
	Total	6	5228.7	Total	6	4660.2

related to the experimental data. As explained in the previous section, in this study, only the power drawn per each ton of grinding media was considered, and the power drawn based on breakage of particles kinetics was not investigated.

3- RESULTS AND DISCUSSION

Variations of the mill power as a function of grinding media weight for simple and grooved rods are demonstrated in Figure 2. As the grinding media weight and mill speed increase, the power consumption for both rod types increase, too. At low speed (40% Critical speed), the power consumption for grooved rods is higher than for simple rods. At medium speed (60% Critical speed), this value is roughly equal and at high speed (80% Critical speed), power consumption for grooved rods is lower than for simple rods. The obtained results can be described as follows.

1: Motions of grinding media on the lifter face

2: The interaction of the individual components of the grinding media together

Generally, the motions of grinding media are influenced by their shapes. On the liner, they are mainly characterized by a series of rolling and sliding motions on the lifter face. Figure 3 illustrates the nature of the contact of simple and grooved rods with the liner surface schematically in a cross-section. In Figure 3-A, it can be seen that the simple media is in contact with the liner surface only at one point or there is only one support point between the simple rod and the liner surface. In this case, the rolling motion is probably greater than the sliding motion and the rods will leave the liner surface sooner. But this effect is investigable for grooved media in two cases. In the first case, the grooved media as simple media is in contact with the liner surface only at one point (Figure 3-B). In the second case, the grooved media is in contact with the liner surface at two points or there are two support points between media and liner surface for every rod (Figure 3-C). In fact, due to the existence of these two support points and the increase of friction between the grinding medium and the liner, the grooved rods resist against rolling motion. Under these conditions, the effect of sliding motion is likely to be dominant. In this type of motion, the departure of media from liner

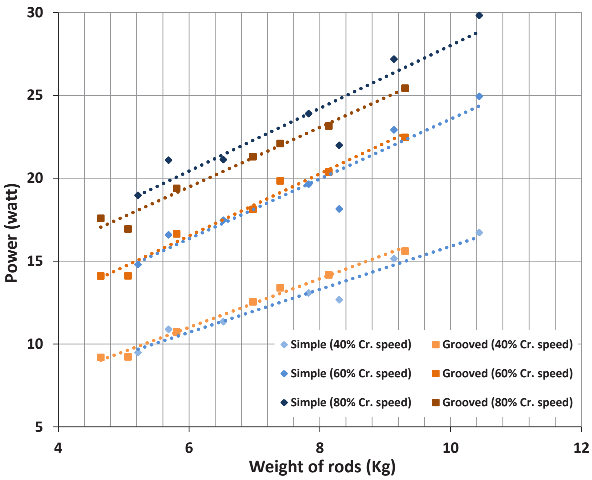

Figure 2. Variations of the mill power as a function of grinding media weight

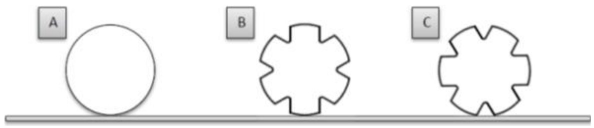

Figure 3. A schematic representation of the contact mechanisms of the investigated grinding media with a liner and/or a lifter

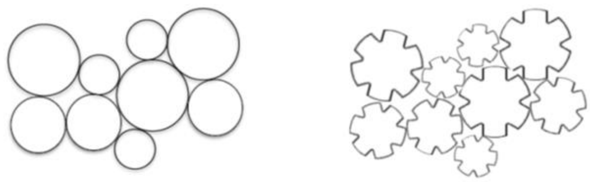

Figure 4. A schematic representation of the interaction and interlocking between the individual grinding media

surface occurs with more delay and the liner and lifter transfer the media to a higher point on the shoulder. This would be a reason for the increase in the degree of cataracting of the charge. On the other hand, the interaction of the individual components of the grinding media together influences the movement of the media in the mill environment. It can be seen in Figure 4. that the interlocking probability of grooved rods is greater than the simple rods. Since the rods with different diameters are used and each groove is created to fit the diameter of each rod, the impactor step of the smaller rod may get stuck inside the groove of the larger rod. This reduces the rolling motion and increases the sliding motion. Based on what was explained above, the dominant motion of grooved grinding media on the liner surface is sliding motion. On the other hand, due to the interaction of individual components of grooved grinding media together, the effect of sliding motion is increased. In this type of motion, the departure of media from liner surface occurs with more delay and the liner and lifter transfer the media to a higher point on the shoulder. In this condition, the grooved grinding media are placed in the lifting area more than the simple grinding media, and this is the reason for the increase in the power draw when using of grooved grinding media. On the other hand, it has been found that the sliding motion occurs at lower speeds [33]. Therefore, at low speed (40% Critical speed), the power drawn by the grooved grinding media is more than the simple grinding media. At medium speed (60% Critical speed), due to the conversion of the movement from sliding to rolling, when using two grinding media, the power draw of mill is equal approximately. At high speed (80% critical speed), although the grooved grinding media are lifted to a higher area, in comparison to the simple grinding media, but due to the reduction of sliding movement contribution and the falling of the grooved grinding media in a higher area of the toe, the torque increases, which in turn has a positive effect on reducing the power draw when using the grooved grinding media. Therefore, in high speed, the power drawn by the grooved grinding media is lower than the simple grinding media.

In order to determine the significant difference in power draw between simple and grooved rods, repeating tests were performed with 95% confidence interval.

The effect of grinding media shape on the specific power draw due to operational parameters such as the mill speed and the fractional mill filling by the media was analyzed. The curves presented in Figure 5 and Figure 6 show the variation of the specific power draw for the fractional mill filling by media of 15.5%, 18.5% and 25% with different mill speed.

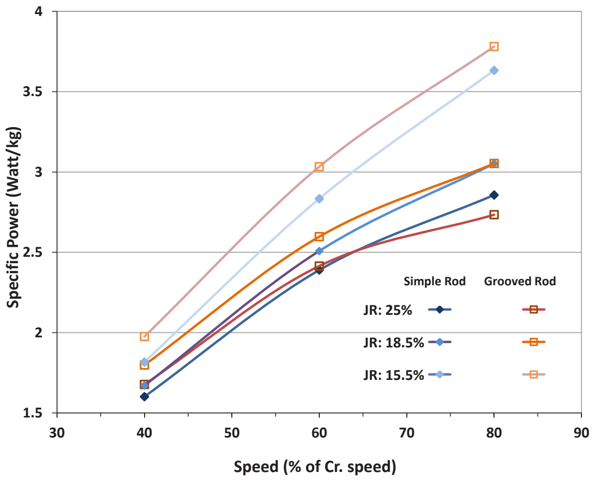

Figure 5. Variations of the specific power with the mill speed at different media filling

According to Figure 5, the results show that in all of the speeds, the highest specific power draw is related to the grooved rods in 15.5% of filling. The maximum specific power draw values for the grooved rods at low (40% critical speed), medium (60% critical speed) and high (80% critical speed) speeds are equal to 2, 3 and 3.8 Watt/kg, respectively. But these values are measured for the simple rod equal to 1.8, 2.8 and 3.6. Also, the specific power increases with increasing the speed, but the specific power rate decreases with increasing the speed and increasing the media filling (J_r). In fact, Figure 5 shows that the specific power becomes more sensitive to the media shape (especially grooved rod) as the mill speed and media filling (J_r) increase.

Experimental data indicate that at 40% (low) and 60% (medium) of critical speeds, the specific power draw by the grooved rods is higher than that simple rods at all grinding media filling studied; However, at 80% (high) of critical speed, the specific power draw by grooved rods decreases but the drawn by simple rod is still increasing. In fact, with increases of the speed and the fractional mill filling by media, the rate of specific power draw decreases faster than the simple rod when using grooved rods, so that at 80% speed and 25% filling, the specific power draw of the grooved rod is less than the simple rod. Lameck et al. stated that, this effect can also occur by varying the position of the grinding media within the mill.

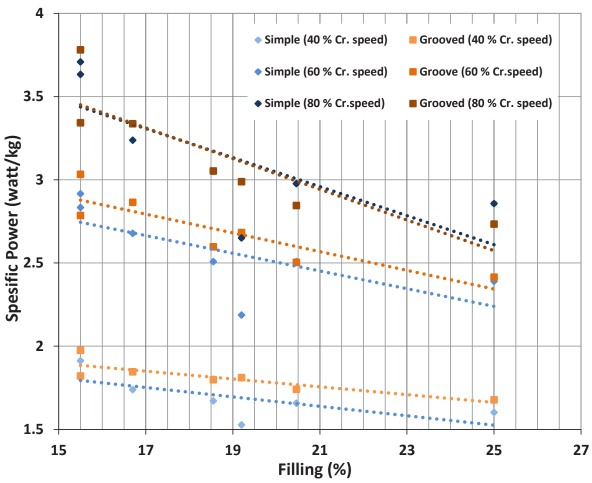

Figure 6. Variations of the specific power with the fractional grinding media filling

These positions have been defined as shoulder and toe [25]. As the mill speed increases, more energy is returned by grinding media at the toe position, which reduces power draw. When using grooved rods, significant variations in the mill power draw can be imagined by changing the grinding media positions inside the mill, especially at high speeds; for example, by changing the shoulder and toe positions, cascading and cataracting movement, as well as the amount of media dispersion.

According to Figure 6, the results of the experiments shows the sensitivity of the mill power draw to mill filling at different fractional mill filling by media. The degree of sensitivity (line slope) increases with the increase in the mill speed. In fact, with increasing the speed, the effect of the fractional mill filling by media on the specific power draw increases. It can also be concluded that the effect of the speed on the specific power draw is greater than the fractional mill filling by media. It can be seen that at mill speed of 80%, the mill power draw is reduced more quickly. At mill speeds of 40% and 60%, the power draw by grooved rods in all of the fractional mill filling by media is higher than simple rods, but at the mill speed of 80% and low fractional mill filling by media, the power draw by both grooved rods and simple rods is similar. However, with the increase in the fractional mill filling by media, the value of the power draw for grooved rods has been shown to be slightly less than that of the simple rods. This effect can also be seen from Equation 3. When comparing these two shapes and in an equal weight of media, the filling percentage of the grooved rods is greater than that of simple rods; thus when using grooved rods, the mill power draw will be reduced. The reason of this could be the reduction of friction and interlocking between individual grinding media and existence of media with mill liners in high speeds. The fading out of the media filling effect at low speeds is probably due to the lack of proper handling, multiple interactions and correlation between individual grooved media and between grooved media and mill liners.

The significant point is the inverse relation of the specific power with the fraction of grinding media filling. This effect is also evident in the model presented by Rowland and Kjos in Equation 3 for the determination of the power drawn by a rod mill in kWh/tone of rods. As mentioned above, the specific power increases as the speed increases, but the specific power rate decreases as the speed and the media filling (J_r) increase. In fact, Figure 5 shows that the specific power becomes more sensitive to the media shape as the mill speed and the media filling (J_r) increase. Also, the comparison of information presented by Lameck et al. [25] in the case of the evaluation of grinding media shapes effects on load behavior and the mill power in dry ball mill and the data of the present research, confirm the accuracy of this issue.

Because of the importance of Equation 3, the predicted power draw values are calculated using this model. The calculated power draw values are also compared with the experimental power draw values. The results are demonstrated in Figure 7. The prediction of the mill power draw using the Rowland and Kjos empirical model Equation 3 in the range of low and medium speeds is more reliable. Therefore, using Equation 3 at low speeds is perfectly valid. As speed increases, its credibility decreases.

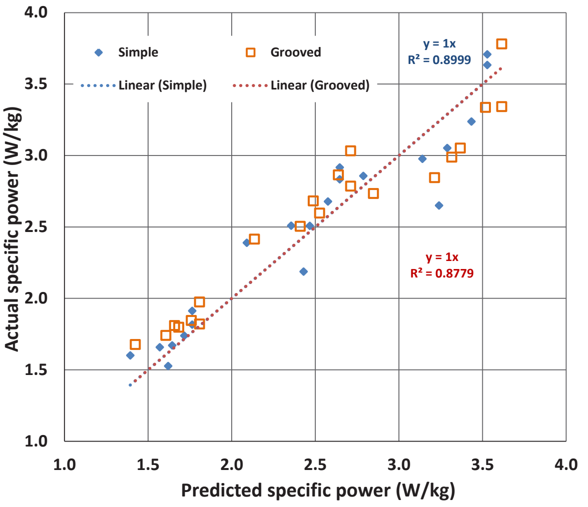

Figure 7. Comparison of the experiment power and the predicted power

4- CONCLUSION

The effect of the grinding media shape on the mill power draw has been proven. The mill power values for both of the studied shapes (simple and grooved rods) were calculated by changing the mill speed and the fractional mill filling by media. The power drawn by two media was different. The power values increased in both of the grinding media with increases in the weight of media and mill speed. The grooved media had a higher specific power draw at low and medium speeds (40% and 60% of critical speed), but at high speeds (80% of critical speed), the specific power consumption for grooved rods was lower than for simple rods. Also, the specific power rate decreased as the mill speed and grinding media filling increased. While at low speeds, the effect of grinding media filling on the power was less. In fact, with increasing the speed, the effect of the fractional mill filling by media on the specific power draw increased. Also, the effect of the speed on the specific power draw was greater than the fractional mill filling by the media.

The mill power draws sensitivity to the media filling increased with the mill speed increasing. In other words, by increasing the grinding media filling at high speed, the specific power rate decreased with more intensity in comparison with other speeds. Generally, with increasing the mill speed and the grinding media filling, the performance of the grooved rod increased more than the simple rods in terms of the power consumption.

Investigations showed that the results do not correspond to what was stated in the hypotheses of the study. In fact, with the geometric deformation of the grinding media, all the changes created in the grinding media such as weight, surface, bulk density, contact mechanisms of the grinding media and the interactions between them (either with each other or with liners) must be considered.

The results showed that improving one feature, due to the deformation of the grinding media, may cause a negative change in other features.

For example, in comparing the same simple and grooved media, it is true that the weight of the grooved media is reduced, but the contact mechanism of them (with each other or with the liner) is different.

Evaluating various parameters, such as the shape of grinding media on the mill power draw, can provide useful information for comprehensive models of power and thus improve the milling performance. Research that combines the above findings with investigating the effect of grinding media shapes on the mill power draw in rod mills, using modern simulation models such as the discrete element method (DEM) in order to observe the load behavior can result in some interesting works in the future. Also, the comparison of the worn rods (simple or grooved) with each of the studied shapes and also their combined effect in order to create real conditions of rod milling process, is suggested for future works.

5- ACKNOWLEDaGMENT

This research was sponsored by the Ministry of Science, Research and Technology of the Islamic Republic of Iran and the Julius Kruttschnitt Mineral Research Centre (SMI-JKMRC), within the Sustainable Minerals Institute, the University of Queensland, Australia. The authors would like to thank SMI-JKMRC for their financial and technical support.

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نشریه مهندسی منابع معدنی، سال ۱۴۰۳، دوره نهم، شماره ۲، ص ۹۱-۸۱

نشریه مهندسی منابع معدنی
Journal of Mineral Resources Engineering (JMRE)

دوره نهم، شماره ۲، تابستان ۱۴۰۳، صفحه ۸۱ تا ۹۱
Vol. 9, No. 2, Summer 2024, pp. 81-91

علمی-پژوهشی

تاثیر شکل واسطه خردایش بر توان کشی آسیای میله‌ای خشک

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دریافت: ۱۴۰۱/۰۷/۰۶ پذیرش: ۱۴۰۱/۰۸/۱۷

چکیده

یکی از اجزای جدایی‌ناپذیر فرآیند آسیاکنی در آسیاهای گردان، واسطه‌های خردایش مورد استفاده در آنها است. علیرغم سادگی شکل‌های واسطه‌های خردایش در آسیای گردان، تاثیر آن‌ها بر عملکرد شکست و همچنین مصرف توان آسیا، به عنوان یک مشکل پیچیده باقی مانده است. سهم زیادی از مصرف انرژی در کارخانه‌های فرآوری مواد معدنی مربوط به عملیات آسیاکنی می‌شود، بنابراین بررسی میزان مصرف توان در این بخش بسیار مهم است. این مقاله به مقایسه اثرات میله‌های معمولی و شیاردار بر توان مصرفی آسیای میله‌ای خشک در سرعت‌ها و پر شدگی‌های مختلف می‌پردازد. نتایج نشان داد که با افزایش وزن واسطه‌های خردایش و سرعت آسیا، توان مصرفی برای هر دو نوع واسطه خردایش مورد مطالعه افزایش و نرخ توان ویژه با افزایش سرعت و پرشدگی واسطه‌های خردایش کاهش یافت. با افزایش سرعت آسیا، حساسیت توان کشی ویژه به پرشدگی واسطه‌های خردایش افزایش یافت. توان کشی ویژه میله‌های شیاردار در سرعت‌های کم و متوسط، بیشتر از میله‌های ساده بود، اما در سرعت‌های بالاتر از ۶۰ درصد سرعت بحرانی، توان کشی ویژه میله‌های شیاردار کمتر از میله‌های ساده بود. با استفاده از یک مدل تجربی، مقادیر تجربی و مدل مقایسه شدند. نتایج نشان داد که پیش‌بینی توان کشی آسیا با استفاده از مدل تجربی ارایه شده در محدوده سرعت‌های پایین و متوسط قابل اعتمادتر است، بنابراین استفاده از این مدل در سرعت های پایین کاملا معتبر است و با افزایش سرعت آسیا از اعتبار آن کاسته می‌شود.

کلمات کلیدی

آسیای میله‌ای، توان کشی، شکل، واسطه خردایش.

استناد به این مقاله

خانی خرشکی، م.، کارآموزیان، م.، یحیایی، م.؛ ۱۴۰۳؛ "**تاثیر شکل واسطه خردایش بر توان کشی آسیای میله‌ای خشک**". نشریه مهندسی منابع معدنی، دوره نهم، شماره ۲، ص ۹۱-۸۱.

DOI: 10.30479/JMRE.2022.17908.1606

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