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Assessing the efficacy of grooved grinding rods as lifters in a laboratory rod mill

Majid Khani Khereshki [a], Mohammad Karamoozian [a,*], Mohsen Yahyaei [b]

[a] *Faculty of Mining, Petroleum and Geophysics Engineering, Shahrood of University Technology, Shahrood, Iran.*

[b] *The University of Queensland, Sustainable Minerals Institute, Julius Kruttschnitt Mineral Research Centre (SMI-JKMRC), Australia.*

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ABSTRACT

To date, limited research has been conducted comparing the effects of different grinding media shapes on milling kinetics, load behaviour, and mill power draw. However, no research has explored their impact on lifter functionality. This study aims to bridge this knowledge gap by investigating the influence of grinding media shape on the lateral movement of the charge (comprising grinding media and material). This analysis involves examining specific breakage rate parameters in a laboratory dry rod mill, shedding light on how grinding media can function as lifters. In this investigation, two types of grinding media, namely simple and grooved rods, were compared. The specific breakage rate parameters were determined using the Austin model. The values associated with the μ parameter, which indicates an increase in the lifting of grinding media with its rise and a corresponding decrease in the specific rate of breakage, were found to be 3758.76 and 4144.63 for simple and grooved rods, respectively. The results demonstrate that, even though grooved rods exhibit a lower specific breakage rate than simple rods, they exhibit strong lifter characteristics. Specifically, they induce a pronounced cataracting effect in the charge.

Keywords: *Rod mill, Media shape, Lifter, Specific breakage rate.*

1. Introduction

In a tumbling mill, the energy required to break minerals is derived from the mill's rotational energy. This energy, generated by the mill liners and lifters, is transferred to the grinding media in the form of both kinetic and potential energy. During the operation, the grinding media are elevated during the climbing phase of the mill's rotation. Once they reach a state of equilibrium, they descend and engage in a tumbling motion over the charge, ultimately fracturing individual mineral particles. This dynamic process is commonly referred to as "charge motion" and has been extensively discussed in previous studies (Austin et al., 1984; Cilliers et al., 1994; King, 2000; Yahyaei and Banisi, 2010). Fig. 1 shows a schematic image of the charge motion in a tumbling mill.

The influence of liner and lifter shapes, as well as mill speed, on breakage mechanisms is clearly observable. When employing smooth liners at lower mill speeds, the grinding media tends to migrate towards the toe position. This cascading motion of the grinding media results in the production of a finer product but also leads to increased liner wear. Conversely, at higher speeds and/or with the inclusion of lifters, the lifting action of the liners becomes more pronounced. The use of smooth liners enhances the abrasion mechanism, consequently promoting the production of finer particles. When lifters are introduced, they further enhance the lifting action of the liners, leading to an increase in the impact mechanism and, consequently, the production of coarser particles (Wills and Finch, 2015; Yahyaei and Banisi, 2010).

Vermeulen and Howat have noted that mills equipped with smooth liners exhibit higher abrasive interactions compared to mills with lifters. However, when lifters are used, the amount of grinding media in flightincreases. In this scenario, the intensity of impactive interactions within the mill also rises (Vermeulen and Howat, 1988).

It has been observed that a lower impact force tends to promote particle breakage. Consequently, an excessive increase in the cataracting load can negatively impact milling performance, affecting both mineral particle breakage (Simba and Moys, 2014) and the costs associated with damaged liners due to the direct impact of grinding media on liners and lifters in the impact zone (Yahyaei and Banisi, 2010). Furthermore, the failure of grinding media can occur, especially in the case of rods used in a rod mill.

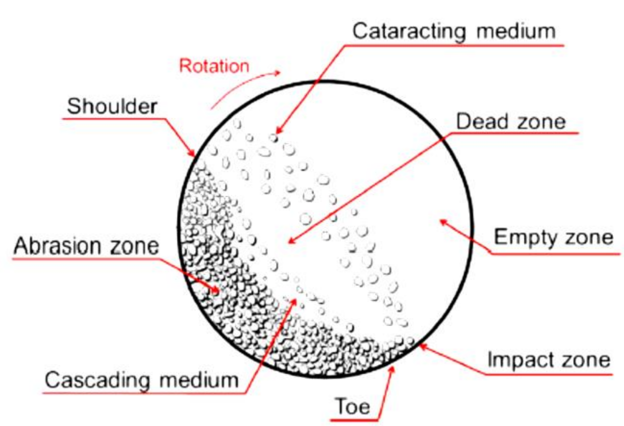

Fig. 1. Schematic image of charge motion in tumbling mill (Wills and Finch, 2015).

* Corresponding author: *E-mail address:* m.karamoozian@shahroodut.ac.ir (M. Karamoozian).

The motion of the charge inside the mill is influenced by various factors, including the liner profile, lifter design, and frictional forces (Powell, 1991; Yahyaei and Banisi, 2010). Additionally, it is impacted by the interactions between the grinding media, liners, and lifters. These interactions and interlockings are strongly affected by contact mechanisms, which can be point, linear, or surface contacts among the media themselves and/or with the liners and lifters (Lameck et al., 2006).

Furthermore, variations in grinding media shape can have effects on their packaging (Zhou et al., 2002), contact mechanisms (Ipek, 2006; Shi, 2004), surface area, weight (Shi, 2004; von Krüger et al., 2000), and ultimately on the charge motion and milling performance. Grinding media constitute a vital element in the milling process, playing a crucial role in the comminution of particles within mineral processing plants, such as flotation circuits (Cao et al., 2021; Meng et al., 2021; Yao et al., 2019; Zhang et al., 2020). The impact of grinding media shape on milling kinetics has been the subject of previous investigations. These studies have examined specific breakage rates, breakage distribution functions, load behavior, mill power draw (Ipek, 2006; Kiangi and Moys, 2008; Lameck et al., 2006; Qian et al., 2013; Shahbazi et al., 2020; Shi, 2004; Simba and Moys, 2014; von Krüger et al., 2000), and even explored their effects on flotation performance (Wang et al., 2022).

However, it is worth noting that to date, no study has reported on the performance of grinding media in the role of lifters. This gap in research makes the investigation into the behavior of grinding media as lifters, as detailed in your previous text, particularly valuable in advancing our understanding of the dynamics within milling processes.

To achieve optimal charge motion control in a grinding process, it is imperative to design the liners and lifters in accordance with the shape of the grinding media. This consideration becomes even more critical when dealing with rod mills. In the context of rod mills, it is essential to select liners that do not disrupt the axial mixing of rods, as this can significantly impact the overall milling performance.

A unique and intriguing aspect of this article lies in its exploration of the influence of grinding media shape on the lateral movement of the charge, which comprises both grinding media and material. Additionally, the study delves into how grinding media can function as lifters through an analysis of specific breakage rate parameters in a dry rod mill.

It is postulated that the interaction and interlocking of grooved rods are more pronounced compared to simple rods. These interactions can lead to an increased cataracting motion, enhancing the milling dynamics. Furthermore, the grooves created on the rods serve as suitable channels for the transfer of minerals to the upper portion of the mill. This innovative perspective sheds light on the intricate relationship between grinding media shape, charge motion, and mineral transport within the mill, providing valuable insights for optimizing milling processes.

This article's intriguing aspect lies in its examination of how grinding media shape influences lateral charge movement and its role as lifters, analyzed through specific breakage rate parameters in a dry rod mill, providing valuable insights for milling optimization.

It is assumed that the interaction and interlocking of grooved rods are further rather than simple rods and these parameters can increase the cataracting motion. Also, the created grooves on the rods are appropriate spaces for the transfer of minerals to the top of the mill.

2. Materials and methods

2.1. Grinding media

In the conducted experiments, two types of rods served as the grinding media: traditional simple rods typically employed in rod mills, and grooved rods. These grooved rods featured a near-star-shaped cross-section with six expanded grooves along each rod, with each groove measuring 0.15 times the rod's diameter. The length of these grinding media was 34 cm. Three different size diameters (25, 20, and 15 mm) were utilized for each type of grinding media. The specific gravity of the media under investigation was 7.83 g/cm3. For reference, Fig. 2 displays images of both the simple rods and grooved rods used in the study.

2.2. Experiment material

In the conducted experiments, seven distinct mono-sized feed fractions of the copper-gold sample, possessing a specific gravity of 2.7 g/cm^3, were employed. The size fractions of the ore sample are detailed in Table 1. To ensure the samples' monosize characteristics, screen series size intervals were selected based on the fourth root of 2 ($\sqrt[4]{2}$).

2.3. Experimental method

A laboratory-scale dry rod mill, featuring a diameter of 17.78 cm and a length of 35.56 cm, was employed in the experiments. The mill had a total volume of 8530 cm^3 and was equipped with six trapezoidal-type liners. These liners had a face angle of 30°, a lifter height of 0.7 cm, and a base width of 1 cm. The mill's operational speed was set at 60 RPM, equivalent to 55.5% of its critical speed, where centrifugal forces balance gravitational forces on the mill shell's inside surface, preventing any load from falling off.

For each experimental run, 12 rods were utilized with a fractional rod filling of 25% (Jr = 25%). To maintain consistent laboratory conditions, both sets of grinding media were ensured to have the same size distribution for the rods. The fraction of mineral filling in each experiment corresponded to the 100% porosity volume of the grinding media (U = 100%).

Grinding experiments were conducted using seven mono sized fractions, each subjected to varying grinding durations of 1, 2, 4, 8, and 16 minutes. Subsequent to the grinding tests, the samples were extracted from the mill and sieved for a duration of 10 minutes using a Rotap sieve shaker to assess the particle size distribution. To gauge experimental precision with a 95% confidence level, selected experiments were replicated. A summary of the milling conditions is provided in Table 1.

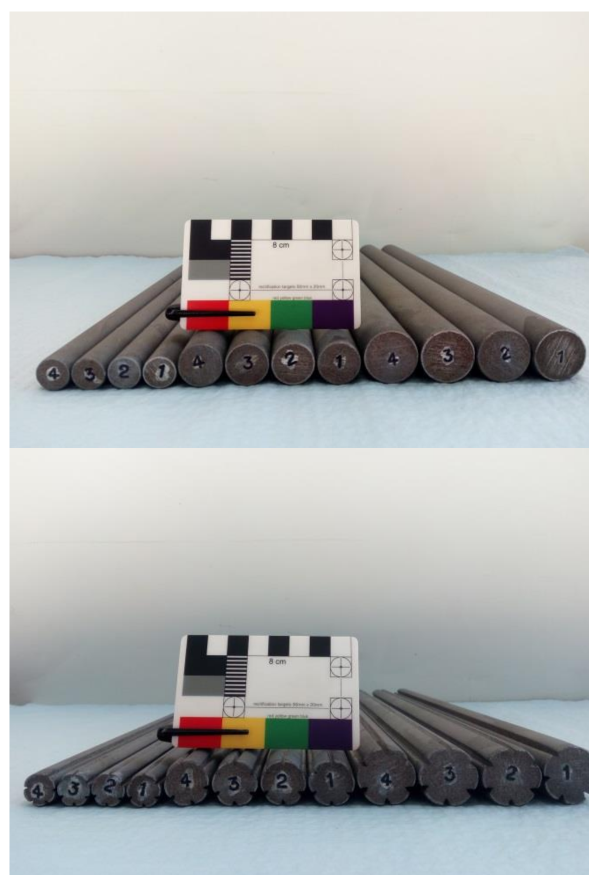

Fig. 2. Images of simple and grooved rods used in experiments.

Table 1. Mill's characteristics, material and test conditions.

Parameters	
Type of the element	Copper- Gold
Feed Size (mm)	-4.75+4.00, -3.35+2.80, -2.36+2.00, -1.7+1.40, -1.18+1.00, -0.85+0.71, -0.60+0.50
Grinding Media	Simple and Grooved Rod
Rod weights	Simple Rod (10.456 kg), Grooved Rod (9.322 kg)
Media Diameter (mm) × No.	25×4, 20×4, 15×4
Media Length (cm)	34
Grinding Times (min)	1, 2, 4, 8, 16
Revolution Counter (RPM)	60
Mill Speed (Critical Speed %)	55
Mill Diameter (cm)	17.78
Mill Length (cm)	35.56
Mill Volume (cm³)	8530
Lifters Type × No.	Trapezoidal × 6
Lifter Face Angle (degree)	30°
Lifter Height (cm)	0.7
Lifter Base Width (cm)	1
Fractional Rod Filling, Jr (%)	25
Material Fractional Filling,U (%)	100

3. Results and Discussion

The specific breakage rate (Si) parameters for both simple and grooved rods were derived using the Austin method, following Equations (1 and 2) (Austin et al., 1984). To obtain the optimal model parameter responses, a non-linear regression method was employed, aiming to minimize the sum of square errors between the experimental and predicted data, as described by Katubilwa and Moys (2009). The obtained results are summarized in Table 2. The graphical representation of the variations in specific breakage rates at different particle feed sizes for the two types of grinding media studied can be found in Fig. 3.

$$S_i = a({}^{x_i}/_{x_0})^{\alpha} Q_i \text{ and } Q_i = [1/(1 + (x_i/\mu)^{\Lambda})] \qquad (1)$$

$$\mu = \left({}^{(\Lambda - \alpha)}/_{\alpha}\right)^{1/\Lambda} x_m \qquad (2)$$

Where S_i represents the specific breakage rate in $\frac{1}{min}$, x_i is the upper limit for size interval in mm and x_0 refers to the reference size (usually 1 mm). also, a and α are defined as the specific breakage rate parameters. Equations 1 and 2 are the functions of mill conditions and material properties, respectively. Parameter a is also named the specific breakage rate. Q_i is known as a correction factor based on the breakage zones.

Also, μ is the particle size when $Q_i = 0.5$ and depends on mill performance and conditions (such as rotational speed, lifter design, grinding media load, and size) as parameter a. Λ is an index that depends on the characteristics and specifications of the materials which expresses the variations of specific breakage rate by particle size variation; so that the specific breakage rate decreases with increasing of particle size in the abnormal breakage zone. x_m is the largest particle size that can be broken by grinding media.

As depicted in Fig. 3, the experimental findings indicate that the specific breakage rate (parameter a) decreases when grooved rods are employed in comparison to simple rods.

Moreover, there is a notable alignment between the values of μ and xm for both types of grinding media. This alignment aligns with Simba and Moys' assertion that lower μ values correspond to higher breakage rates and more stable load behavior during milling (Simba and Moys, 2014). Additionally, the degree of cataracting in the load (comprising grinding media and ore) is directly linked to the μ parameter. Specifically, an increase in μ signifies a heightened degree of cataracting in the charge (Simba and Moys, 2014). Notably, grooved rods exhibit the highest value of μ, indicating the highest degree of cataracting in the charge (4144.63 for grooved rods and 3758.76 for simple rods).

Table 2. The values of specific Breakage rate Parameters.

	Parameters	Simple Rod	Grooved Rod
Specific Breakage Rate (S)	α	0.58	0.26
	a	0.67	0.29
	μ	3758.76	4144.63
	Λ	4.68	8.54
	X_m (μm)	2479.37	2767.86

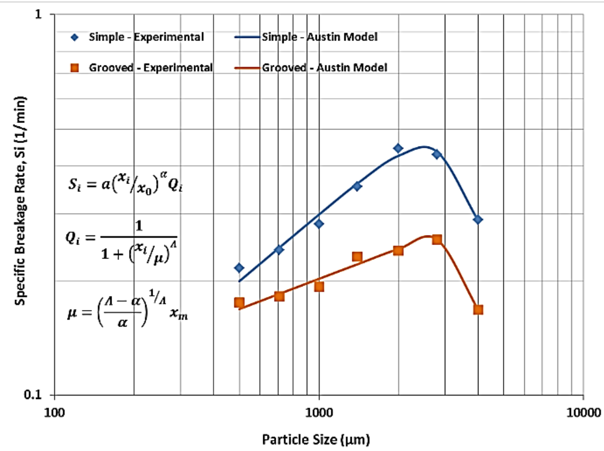

Fig. 3. Variation of the specific breakage rate with particle size for simple and grooved rod.

To validate these findings, similar experiments were conducted using homogeneous silicate ore. The results of these experiments also confirmed an increase in the cataracting of the load and a decrease in the specific breakage rate when grooved rods were employed. Specifically, the μ parameter for grooved rods and simple rods was calculated at 3813.42 and 1984.75, respectively. Additionally, the values of parameter a for grooved and simple rods were determined to be 0.52 and 2.17, respectively.

Indeed, lower values of μ are indicative of higher breakage rates and a more stable load behavior during milling operations, as emphasized by Simba and Moys (2014). The degree of cataracting in the load, consisting of both grinding media and ore, is intimately linked to the values of the μ parameter.

According to Table 2, the μ values for grooved rods are notably higher than those for simple rods. This observation finds further support in the experimental results (Table 2, including μ and a values) and additional evidence, such as the extension of grinding media on the liner due to the angle of repose and an analysis of the individual components of grinding media motion.

Moreover, this result is corroborated by the parameter a values, indicating that the cataracting motion of grooved rods is sufficiently high to reduce the number of impacts on minerals, causing them to directly collide with the liner surface or lifter. In such a scenario, a reduction in cataracting motion would be advantageous to enhance the specific breakage rate.

To optimize the performance of grooved rods in terms of breakage rate, it is advisable to consider using smooth liners and/or liners equipped with lifters featuring a higher face angle. This strategic adjustment can potentially yield improved milling outcomes.

The enhanced performance of grinding media acting as lifters and the promotion of charge cataracting can be attributed to alterations in the movement behavior of the grinding media arising from the variation in their shape. Additionally, the lifting of minerals is facilitated through the grooves, leading to what can be termed as a "spoon action." This spoon action of grooved grinding media is visually illustrated in Fig. 4, providing a clear depiction of the mechanisms at play.

Fig. 4. The spoon action of grooved grinding rods in rod mill.

Traditionally, it has been a widely accepted notion that at mill speeds less than or equal to 60% of the critical speed, the repose angle can serve as a reliable means to estimate the charge cross-section, including the positions of the shoulder and toe, or more broadly, the charge position (Lameck et al., 2006). Fig. 5 illustrates both the angle of repose and the distribution of the studied grinding media on the mill liner surface. Notably, the visualization demonstrates that grooved rods exhibit a greater degree of dispersion compared to simple rods.

The introduction of lifters has the effect of increasing the angle of repose, as highlighted by Vermeulen and Howat (1988). Consequently, both the angle of repose and the spreading of grooved rods on the liner surface surpass those observed with simple rods. It's worth noting that the lifters used in the experiments were consistent across both cases; hence, the primary factor contributing to variations in the repose angle and the charge distribution on the liner surface is the shape of the grinding media itself.

Fig. 5. Dispersing of simple rods and grooved rods on the mill liner surface.

In general, the movements of grinding media are significantly influenced by their shape. When they come into contact with the liner, their behavior is primarily characterized by a sequence of rolling and sliding motions on the lifter's surface. Fig 6-A, 6-B, and 6-C provide a schematic representation of how simple and grooved rods interact with the liner surface in a cross-section, illustrating the nature of this contact.

In Fig. 6-A, it's evident that the simple media has a single contact point with the liner surface, essentially relying on just one support point between the simple rod and the liner surface. In this scenario, the rolling motion likely predominates over sliding motion, causing the rods to disengage from the liner surface relatively quickly.

However, when examining grooved media, there are two distinctive cases to consider. In the first case (Fig. 6-B), grooved media, like simple media, makes contact with the liner surface at just one point. In contrast, in the second case (Fig. 6-C), grooved media maintains contact with the liner surface at two points, effectively having two support points between the media and the liner surface for each rod. This dual support point configuration resists rolling motion and, under these conditions, sliding motion is more likely to dominate. As a result, the media remains in contact with the liner surface for a longer duration, and the liner and lifter assist in elevating the media to a higher position on the shoulder. This phenomenon contributes to the increased degree of cataracting within the charge.

Moreover, the interaction among individual components of the grinding media plays a crucial role in influencing media movement within the mill environment. As depicted in Fig. 7, grooved rods exhibit a higher probability of interlocking compared to simple rods. This reduced interlocking probability in simple rods allows rolling motion to prevail. In contrast, the higher interlocking probability among grooved rods reduces rolling motion to some extent, increasing the prevalence of sliding motion. Consequently, this leads to a delayed disengagement from the mill's inner wall and an elevated media position. Given that rolling motion is predominant in simple rods, the interactions among grooved media tend to mitigate rolling motion while increasing sliding motion.

To prevent any potential confusion, it's important to note that this discussion does not account for the tangling of rods, a phenomenon commonly observed in rod mills (Rowland and Kjos, 1978).

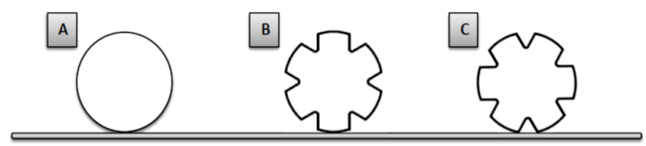

Fig. 6. The schematic image of contact mechanisms of studied grinding media with liner and or lifter.

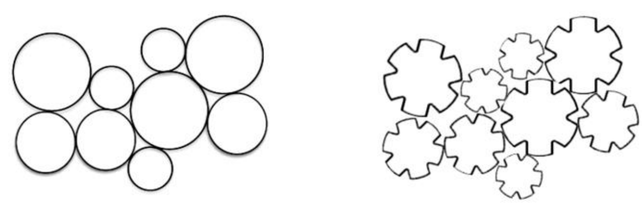

Fig. 7. The schematic image of interaction and interlocking between individual grinding media.

Furthermore, the alteration of charge motion resulting from changes in the geometric shape of grinding media can yield a positive impact on the mill power draw. Additionally, elevating the load and grinding media to a greater height generates increased potential impact energy, consequently enhancing the impact mechanism within the mill.

4. Conclusion

Grinding kinetics experiments were conducted on copper-gold ore to compare two grinding media types with distinct geometric shapes, namely grooved and simple rods. The analysis revealed that specific breakage rate parameters exhibited a decrease when grooved rods were used in comparison to simple rods (0.26 for grooved rods and 0.58 for simple rods). This outcome underscores the dual role of grooved rods, serving as both lifters and grinding media, and this was corroborated through specific breakage rate parameters.

Furthermore, an assessment of the motion characteristics of grooved rods in comparison to simple rods substantiated this finding. Grooved rods exhibited a notably greater extension of grinding media on the mill wall and a higher degree of cataracting motion, as evidenced by the parameter μ (which registered as 4144.63 for grooved rods and 3758.76 for simple rods).

The observed reduction in the specific breakage rate in grooved rods appears to stem from a misalignment between the grooved rod geometry and the trapezoidal lifters employed in the experiments. To enhance the robustness and validity of the research findings, conducting grinding kinetics experiments with smooth liners and/or liners equipped with lifters featuring a higher face angle is recommended. This approach could help provide further insights and clarify the impact of grinding media shape on milling kinetics and performance.

The pronounced spreading of grooved rods along the mill chamber wall exceeded that observed with simple rods. This extensive spreading of grinding media provides valuable insights into the load behavior during the grinding operation.

Moreover, the contact mechanisms of grinding media with both the liner and lifter, as well as their interactions and interlocking, play a fundamental role in the movement process of grinding media within the mill. Importantly, these dynamics are intricately linked to the specific shape of the grinding media in use. Understanding these interactions is essential for comprehending the complex behavior of grinding media during milling processes.

Indeed, the precise design and careful selection of grinding media shape, as well as the appropriate choice of liner and lifter configurations, are crucial factors in meeting the control requirements of the grinding process. These considerations play a pivotal role in optimizing milling operations and achieving desired outcomes in mineral processing and grinding applications.

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