Mining of Mineral Deposits
Volume 17 (2023), Issue 2, 71-81

MMD JOURNAL / MINING.IN.UA

https://doi.org/10.33271/mining17.02.071

Effect of ore heterogeneity on the ball mill wear rate during a grinding process at gold mines of Saudi Arabia (KSA)

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Abstract

Purpose. The current research aims to study the effect of gold ore grinding on the wear rate of grinding balls.

Methods. Six boulder rock samples were selected from some KSA mines; five core samples were taken from each of them to identify the mechanical properties (compressive strength, Young's modulus, and Poisson's ratio). These mechanical properties were applied to identify the hardness class of all 30 core samples. Five samples with different mechanical properties from the same boulder sample were milled to study the effect of the compressive strength difference and grinding time on wear rate. Then, six samples were taken from different regions with similar mechanical properties but different petrographic characteristics. They were also milled under the same grinding conditions to study the effect of the microscopic mineral composition on the wear rate.

Findings. The results showed that the wear rate increased with the improving mechanical properties and with the increasing grinding time. On the other hand, the results based on different microscopic descriptions of the six samples showed that despite similar mechanical properties, the wear rates differed. Petrographic characteristics confirmed the presence of quartz in most of the samples as an associated mineral; it is likely that it has the greatest effect on the grinding ball wear.

Originality. The paper proposes a method for investigating ore heterogeneity, which has a major impact on the wear rate during a grinding process, as well as on the reducing costs and improving efficiency of grinding media.

Practical implications. The research emphasizes the importance of investigating variables (e.g. ore heterogeneity) other than ball size, grinding medium composition, and wet or dry grinding that have a substantial impact on grinding efficiency. The findings could be applied in feasibility studies to calculate and evaluate grinding costs versus grinding efficiency.

Keywords: *Saudi gold mine, gold rock hardness, mechanical properties, petrographic descriptions, wear rate, ball mill*

1. Introduction

Mineral processing and mining industry is a significant part of the economy worldwide. An important characteristic of these industries is that they consume a lot of energy. In particular, it is estimated that in 2012 the metal and non-metal mining industry consumed 150 PJ of energy. The main part of this energy is spent on wear and friction, which provides excellent motivation for studying wear associated with mining [1], [2]. The wear of moving parts (such as grinding balls) is very important while determining the period, during which the metal used can perform its functions effectively. Thus, the higher its rate in the ball is, the lower its efficiency is, meaning that it does not fulfil its function [3], [4]. For this reason, some researchers were interested in improving the properties of wear resistance using high-entropy alloys (HEAs) [5], a lead-bronze/steel bimetal composite [6], alumina-toughened-zirconia materials [7], lead-tin bronze alloy [8] etc. Fernández-Álvarez et al. [9] revealed that adding nanosilica to milling process makes the epoxy-matrix coatings degrade chemically less than the non-reinforced ones under irradiation and thus wear resistance. Zhang et al. [10] predict the influence of ball milling with different parameters on the strength of phosphorus building gypsum by using NSGM (1,4) Model. Attyabi et al. [11] studied the effect of time on microstructure and magnetic properties of Mn52Al45.7C2.3 flakes with different sizes fabricated using a ball-milling method. Sojithamporn et al. [12] used response surface methodology to optimize the mechanical milling process parameters of harmonic-structure pure Cu.

The balls used in the ball mill represent the largest part of the variable costs as they range from 40% to 45% of the total costs of crushing and grinding operations in the mining industry [13]. Ali [14] proved that the operating parameters in ball milling process with increased impact severity led to the improved relative performance of white cast irons. Large quantities of balls are consumed annually in milling operations; that may cost millions of dollars. Moreover, ores that are characterized by high hardness (i.e. gold ores) have a consumption rate of 1 to 2 kg per milled ton [15]. Numerous factors are included in the ideal selection of grinding medium. Essential features comprise rock hardness, feed size, product size, pulp density, pulp level, mill size, mill speed, and feed rate [13]. Although milling is an essential step in many ore processing operations, it is rather costly. The cost

Received: 14 February 2023. Accepted: 12 May 2023. Available online: 30 June 2023

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

of changing the grinding balls was calculated in 1978 for copper production to be $ 0.25/ton [16]. It was concluded that the wear cost of the balls is approximately equal to the energy consumption cost of the grinding process [17]-[20]. In addition, Mahd Ad Dahab gold mine in Saudi Arabia consumes 1200 kg of balls used in grinding media per day. In terms of Mahd Ad Dahab gold mine, the ball wear rate is about 1.2% per day; however, this rate is about 0.3% per day in laboratory tests as the ball mill is laminated with a rubber layer. Sometimes the milling circuit is designed without considering the variables that may occur and affect the efficiency of the grinding process such as changes in throughput, blending patterns, and rock properties [21].

The rate of grinding depends on many factors, including the ones related to the specifications of mill and balls and the ones related to the ore characteristics. As with any feasibility study, when talking about grinding media in a ball mill, it is necessary to obtain the highest possible efficiency and achieve the lowest expected losses. The wear of balls used during a grinding process is considered one of the losses that cause an increase in the operating cost allocated to the ball mill [21]. Ball wear occurs due to abrasion, corrosion, and impact [22]. The removals of metal from the surface of the grinding medium represent the wear resulting from abrasion whereas thin films/layers, which have been abraded away during wet grinding operation, refer to wear that takes place by corrosion [23]-[25]. Pealing, spalling, and notching result as the contact of ore-metal-environment represents wear that occurs by impact [26], [27]. Several studies reveal that the main reason for the wear during a milling process is abrasion, while corrosion accounts for less than 10% of the total wear [28]. The wear results in wet grinding due to abrasion, which is much higher than that occurred in the dry grinding environment [29], [30], while Abdelhaffez [31] stated that the ball wear rate in a wet grinding medium is less than that resulted in a dry medium. Nevertheless, it is hard to separate the contribution of each wear mechanism [31], [32]. The wear of grinding media can be predicted by incorporating the three wear mechanisms into the modelling approach [33]. The mechanical properties of rocks are among the most important causes of wear. For this reason, it is necessary to figure out it in order to select the most suitable material and avoid the costs that may grow due to not studying it well [34]. Many studies have focused recently not only on the accurate measurement of rock hardness and rock abrasivity but also on finding the relationship between them and wear rates [35]. Using regression analysis and artificial neural network, these studies demonstrated strong relationship between rock abrasivity and hardness, on the one hand, and uniaxial compressive strength, direct shear strength, quartz content, and abrasive mineral content, on the other hand [36]-[38].

The paper will analyze the mechanical properties and use them as the basis to identify rock hardness; three approved classifications are to be involved. Then the relationship between those mechanical properties (for rocks of the same petrographic description) will be studied with the wear rates of the balls in a ball mill. Finally, the relationship between the mineral content of different rocks (i.e. different petrographic descriptions) and the wear rates of balls will be considered.

2. Experimental work

Various tests, whether geotechnical, mineralogical, or wear measurements, have been performed in the laboratories of rock mechanics, mineralogy, and mineral processing, respectively; the laboratories are located in King Abdulaziz University. Thirty lump samples have been collected from six different gold mines in Saudi Arabia as shown in Table 1.

Table 1. Total lump samples from different mine locations

Gold mine	Lump samples
Mahd Ad Dhahab Mine	5
Al Amar Mine	5
Ad Duwayhi	5
Bulghah Mine	5
Sukhaybarat Mine	5
Mansourah-Massarah Mine Project	5

In terms of geotechnical tests, five core specimens per location were prepared (5 samples · 6 locations = 30 core specimens) with standard dimensions [39] for their testing under a compression machine (2000 kN) according to [40]. The strain gauges were installed on all specimens to record deformation in the axial and lateral directions during the compression force effect to identify compressive strength (σ_c), modulus of elasticity (Ea), and Poisson's ratio (υ).

In terms of mineralogical tests, the mineralized samples were prepared as thin polished sections to enable their studying both by means of the transmitted and reflected light microscopy. A transmitted light microscope is used to investigate gangue minerals (e.g. silicates, carbonates etc.); a reflected light microscope is used to examine ore minerals (e.g. sulfides, oxides) [41].

Regarding to wear measurement tests, the principle of measuring the weight loss of the balls per time was applied on two different cases. Case one is as follows: dry milling on a group of samples from Sukhaybarat mine, having the same petrographic descriptions, to find out the effect of grinding time and compressive strength on the wear rate of balls. However, case two was also carried out in terms of dry milling but on a group of samples from different gold mines, having different petrographic descriptions to study the effect of mineralogical composition of gold rocks on the wear rate of balls. First, the dimensions of the mill (diameter and height) were measured to determine its size; then, the size of balls to be used was determined basing on the rule that balls should occupy 42% of the total mill space [42].

The sequence that has been followed to determine the wear rate started by preparing 4 kg of crushed rocks of -3.15 + 2.5 mm size. Then the whole quantity is fed to the mill, measured in size, and grinding begins for different periods of time, starting with an hour (average time to ensure that 80% of the total volume fed passes through the sieve -150 microns) and then multiplying exponentially, being 2, 4, 8, then 16 hours.

Before starting a milling process, accurate weight of all balls was determined. Likewise, when a grinding process is completed, all balls are removed from the mill and cleaned of suspended materials; further, they are weighed again accurately to obtain the lost weight as a result of grinding. Each time, a wear rate of the balls is defined with respect to time as in Equation (1) [21], [40]:

$$W.R. = \left(\frac{W_b - W_a}{W_b} \cdot 100 \right), \quad (1)$$

where:

$W.R.$ – wear rate, (%);

W_b – weight of a ball before grinding, (g);

W_a – weight of a ball after grinding, (g).

Figure 1 shows the laboratory tools including boulder samples, sieves, crushed ore, steel balls, electronic balance, and a tumbling mill used during the experimental work.

A more detailed description of how laboratory tools were used to specify the wear rate of grinding balls during the experimental work is as follows:

1. Preparation of crushed rocks: 4 kg of crushed rocks of -3.15 + 2.5 mm size were prepared. This involved crushing rocks into small pieces using a jaw crusher.

2. Measuring the mill size: it was measured using caliber with the accuracy of 0.1 mm.

3. Estimating the required volume of the balls: this step is done by occupying 42% of the mill volume with clean balls.

4. Determining the weight of grinding balls: the weight of all grinding balls was determined before a grinding process began. This was done by weighing all the balls using an accurate weighing scale of 0.1 gm.

5. Grinding process: the mill was then fed with the crushed rock to achieve complete filling of the interstitial voids between the balls. After that, the grinding began for different grinding time, starting with an hour. Then, the grinding periods were multiplied exponentially by 2, 4, 8, and 16 hours.

6. Cleaning the grinding balls: the mill then discharged, and the balls were cleaned from the contaminated stuck materials using alcohol to ensure that the balls were cleaned thoroughly.

7. Determining the weight of grinding balls after grinding: after cleaning, the grinding balls were weighed again using an accurate weighing scale to define the lost weight as a result of grinding.

8. Calculation of the wear rate: the wear rate of the grinding balls was determined using the lost weight of the balls and the grinding time. This was likely done using Equation (1) or a similar formula.

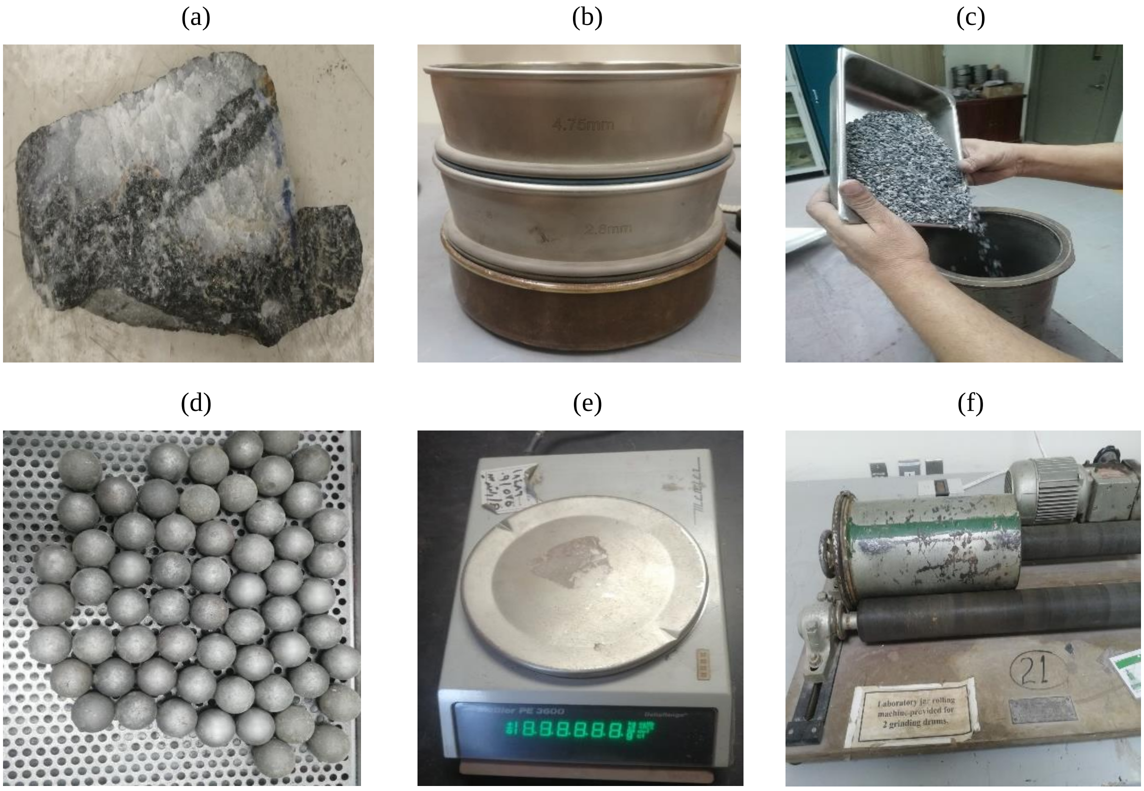


Figure 1. Laboratory tools used during the experimental work: (a) – boulder sample; (b) – sieves; (c) – crushed ore; (d) – steel balls; (e) – electronic scale; (f) – tumbling mill

Throughout the experimental work, various laboratory tools and equipment were used, including a jaw crusher, tape measure, weighing scale, mill, cleaning solution, and cloth/brush for cleaning. The use of these laboratory tools ensured that the experimental work was conducted accurately and consistently; that made it possible to obtain the reliable data on the wear rate of grinding balls.

3. Results and discussions

3.1. Rock hardness

Different mechanical properties (σ, E, and v) were identified for 30 specimens (Table 2). Consequently, based on those properties, three hardness classifications were adapted: classification based on (σ) only; classification based on (σ) with (E); and classification based on (σ) with (E/v) as shown in Table 2.

According to the first classification, it is clear from Table 3 that (σ) values of all the Mahd Ad Dhahab Mine samples are greater than 250 MPa; therefore they are classified as extremely hard. As for the Al Amar Mine samples, four of them gave (σ) values higher than 250 MPa as they are extremely hard also, and only one sample gave a value of 157 MPa, meaning that they are very hard. The Ad Duwayhi Mine samples and the Sukhaybarat Mine samples were similar in that four samples gave a value between 100 and 250 MPa (very hard), while one sample was abnormal and gave the values higher than 250 MPa (extremely hard).

Also, the Bulghah Mine samples were similar to those from Mansourah Massarah Mine – four samples were between 100 and 250 MPa (very hard), and one sample was less than 100 MPa (hard). However, in general, most of the samples are considered as either extremely hard or very hard.

Table 2. Three hardness classifications adapted

Classification based on (σ) only [43]		Classification based on (σ) with (E) [43]		Classification based on (σ) with (E/v) [44]	
Class	(σ), MPa	Class	Modulus ratio	Class	(σ), MPa and (E/v), GPa
Hard	70-100	High	> 500	Weak extremely deformable	10-15
Very hard	100-250	Medium	500 to 200	Moderately strong very deformable	15-50
Extremely hard	> 250	Low	< 200	Strong moderately deformable	50-120
–				Very strong slightly deformable	120-230
				Extremely strong very slightly deformable	230-1000

Table 3. Mechanical properties (σ, E, and v) of different rock samples

Location		Mahd Ad Dhahab Mine					Al Amar Mine				
Sample ID		Md-1	Md-2	Md-3	Md-4	Md-5	Am-1	Am-2	Am-3	Am-4	Am-5
Mechanical properties	σ, (MPa)	255	269	276	291	324	157	261	281	290	308
	E, (GPa)	67	85	72	81	89	56	65	79	65	90
	v	0.29	0.33	0.35	0.36	0.38	0.24	0.28	0.32	0.30	0.37
Location		Ad Duwayhi Mine					Bulghah Mine				
Sample ID		Ad-1	Ad-2	Ad-3	Ad-4	Ad-5	Bu-1	Bu-2	Bu-3	Bu-4	Bu-5
Mechanical properties	σ, (MPa)	148	165	177	212	254	87	176	189	201	255
	E, (GPa)	46	52	57	69	65	34	44	54	63	67
	v	0.23	0.24	0.25	0.27	0.26	0.18	0.24	0.25	0.25	0.26
Location		Sukhaybarat Mine					Mansourah Massarah Mine				
Sample ID		Suk-1	Suk-2	Suk-3	Suk-4	Suk-5	MM-1	MM-2	MM-3	MM-4	MM-5
Mechanical properties	σ, (MPa)	157	185	211	238	257	223	199	175	203	263
	E, (GPa)	51	49	56	62	66	65	53	51	62	68
	v	0.20	0.21	0.24	0.26	0.27	0.19	0.19	0.22	0.24	0.28

On the other hand, two classifications of rock hardness were done based on (σ) with (E) and (σ) with (E/v) as shown in Figure 2 and 3, respectively. Figure 2 demonstrates that almost all samples fall into two classes, being stiff-strong and very stiff-strong; a few samples fall in the classes, being stiff-medium and very stiff-very strong. Moreover, all samples fall in the middle zone described as the average modulus ratio.

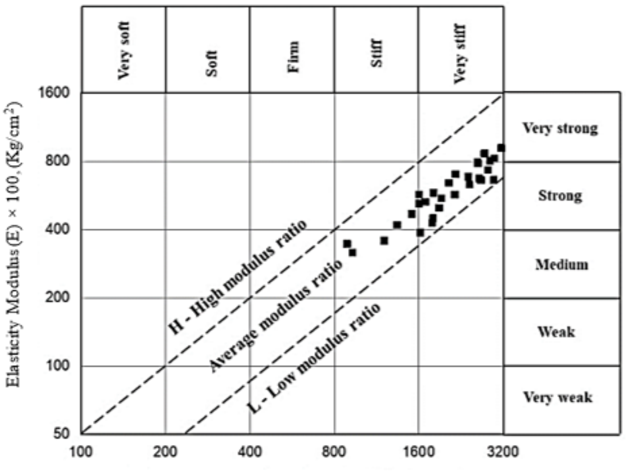


Figure 2. Engineering classification of intact rocks according to the (Deem and Miller 1966) method (Deere and Miller, 1966)

Figure 3 shows that most samples fall in the very strong-slightly deformable (VS-SD) class and the extremely strong-very slightly deformable (ES-VSD) class.

From the three classifications of rock hardness, it can be said that the rocks are very close in their hardness. Consequently, there was an idea to study more thoroughly the mineral content of the rock samples and try to find a relationship between it and the wear rates that occur in the balls inside the mill.

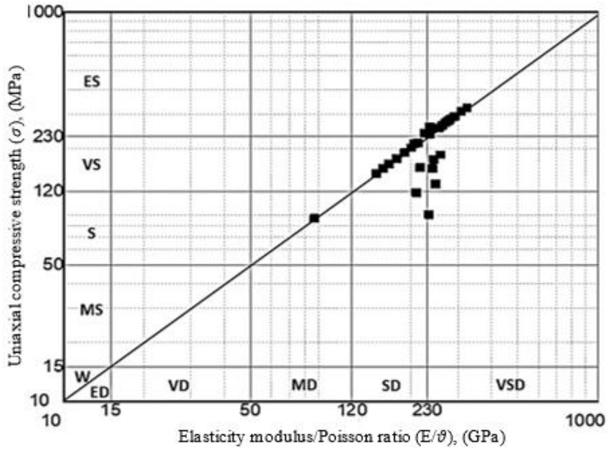


Figure 3. Classifying rocks on a plot of rock strength versus (E/v) according to Türk and Dearman, 1983; W – weak; MS – moderately strong; S – strong; VS – very strong; ES – extremely strong; ED – extremely deformable; VD – very deformable; MD – moderately deformable; SD – slightly deformable; VSD – very slightly deformable

3.2. Study of the wear rates of grinding balls only in terms of rock gold samples from Sukhaybarat Mine

This part was conducted in the context of dry milling and a group of samples from Sukhaybarat Mine at various compressive strength and different grinding time. The average wear rates (%) was calculated using equation 1; the results are represented in Table 4. It is evident from Table 4 (for horizontal rows) that the wear rate of all samples increases with the growing grinding time. All five samples showed a steady increase in the wear rate. One can also note a steady increase in the values of vertical columns, i.e. an increase in compressive strength, except two samples (Suk-2 and Suk-3), which gave lower values compared to sample Suk-1 (157 MPa). That may be due to internal defects in those two samples or because of personal errors in the test procedure.

Table 4. Dry grinding conditions for the Sukhaybarat Mine ore

Sample ID	σ, MPa	Grinding time, (*h*)					Average wear rates of the balls, (%)
		1	2	4	8	16	
		Wear rates, (%)					
Suk-1	157	0.122	0.135	0.184	0.242	0.353	0.2072
Suk-2	185	0.111	0.147	0.202	0.256	0.371	0.2174
Suk-3	211	0.120	0.158	0.218	0.271	0.396	0.2326
Suk-4	238	0.129	0.170	0.229	0.279	0.413	0.244
Suk-5	257	0.136	0.184	0.238	0.291	0.427	0.2552
Average wear rates of the balls, (%)		0.1236	0.1588	0.2142	0.2678	0.392	–

Pictorial figures were made to illustrate the relationship between the wear rate and the grinding time, and between the wear rate and the compressive strength (Figs. 4 and 5, respectively). A simple linear regression model can fit both points of the figures.

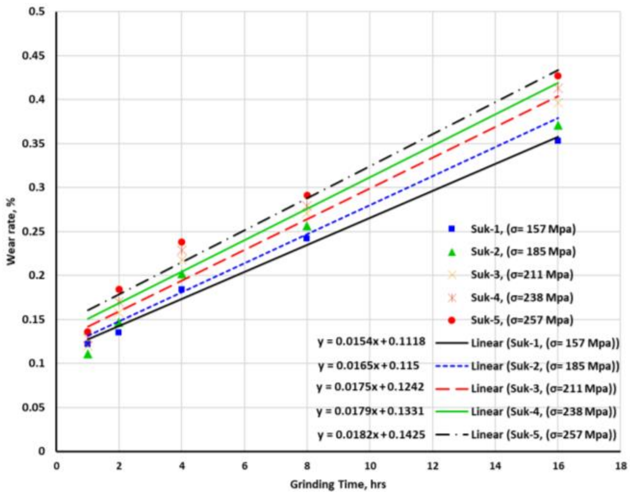


Figure 4. Wear rates of the balls vs grinding time

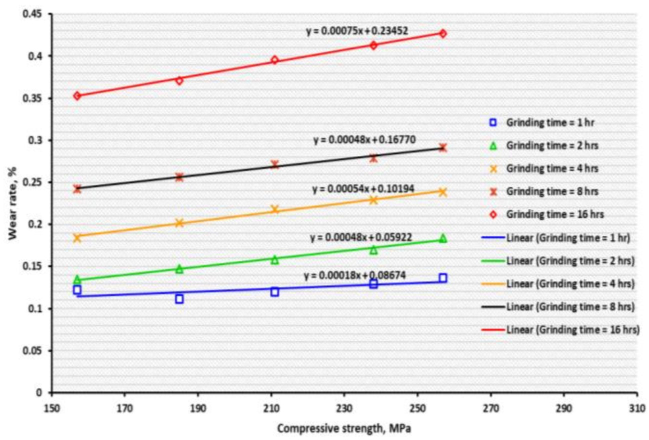


Figure 5. Wear rates of the balls vs compressive strength

By looking at Figure 4 and the equations written on each fitting line in the five samples, it is clear that the value of the coefficient multiplied by *x*, representing the line slope, increases gradually from sample Suk-1 (with σ of 157 MPa) to sample Suk-5 (with σ of 257 MPa). This means that a sample with a higher compressive strength will cause a higher wear rate, not only in magnitude, but also in the rate of change with time, as it is seen from the slopes of the lines.

As for Figure 5, showing the spread of wear values with compressive strength, it can also be seen that as the amount of grinding time increases, the amount and rate of change of wear occurring in the ball increases slightly. The bottom-top appearance of the lines in this order indicates an increasing amount of wear, and growing value of x coefficient (slope) in the equations written on each line indicates an increasing rate of wear change. However, the rate of wear change at grinding periods of time 2 and 8 is almost equal, and the line representing grinding time 4 approaches them, but it increases marginally.

For more clarification, the average wear values (recorded in Table 4) were calculated horizontally and vertically to find a single linear regression equation that represents the wear relationship with both grinding time and compressive strength (Figs. 6 and 7, respectively).

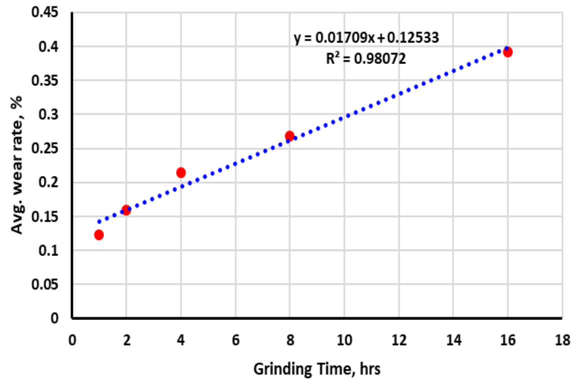


Figure 6. Grinding time vs average wear rates of the balls

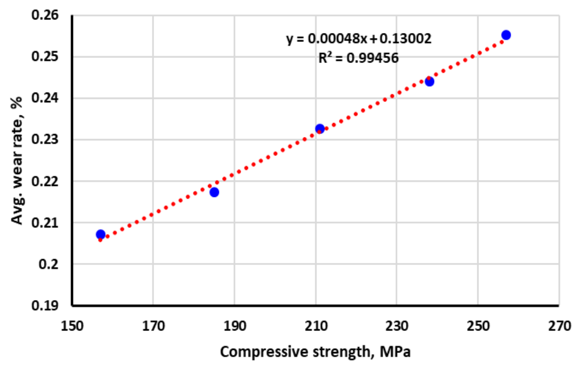


Figure 7. Compressive strength vs average wear rates of the balls

One can note from Figures 6 and 7 that there is a strong linear relationship between the wear rate of the balls and the applied grinding time and compressive strength. Since the value of the coefficient of determination (R^2) in the two lines represented in the two figures is very close to one, this indicates that the fitting line, representing the two spread models, is considered the most accurate and reliable one in predicting the wear rate values. That is true provided that the grinding time is limited between the studied range (from 1 to 16 hours) and in terms of the Sukhaybarat Mine samples.

Moreover, based on the two equations written on the above two lines, the slope of the line, representing the relationship between the wear rate and the grinding time, is greater than the one, representing the relationship between the wear rate and the rock's compressive strength. It indicates that increasing grinding time has a greater effect than the increasing compressive strength. However, the rock that was milled here included five rock samples from Sukhaybarat Mine with the same mineral composition. To study such effects, petrographic properties should be included as it will be seen further.

3.3. Study of wear rates of grinding balls using rock gold samples from six different mines

Relying on the previous conclusion that the wear rates in the Sukhaybarat Mine samples increased along with growing rock's compressive strength, six samples were selected from different mines (Mahd Ad Dhahab, Al Amar, Ad Duwayhi, Bulghah, Sukhaybarat, and Mansourah Massarah) to monitor the similarity of their effect on wear rates. The samples had approximately the same mechanical properties (σ, E, and υ) (Table 5).

3.3.1. Results of the wear rates of balls

The results of wear rate are shown in Table 6. The results revealed that there is a discrepancy in the wear rate values among the six samples despite the equal values of their compressive strength. As it can be noted, the Sukhaybarat Mine sample gave the highest wear rate at different grinding time; it was followed by the samples of Mansourah Massarah, Bulghah, Ad Duwayhi, Mahd Ad Dhahab, and Al Amar mines (Fig. 8).

Table 5. The selected rock samples

Mine location		Mahd Ad Dhahab	Al Amar	Ad Duwayhi	Bulghah	Sukhaybarat	Mansourah Massarah
Sample ID		Md-1	Am-2	Ad-5	Bu-5	Suk-5	MM-5
Mechanical properties	σ, (MPa)	255	261	254	255	257	263
	E, (GPa)	67	65	65	67	66	68
	υ	0.29	0.28	0.26	0.26	0.27	0.28

Table 6. Dry grinding conditions of samples from different gold mines in KSA

Mine location	Sample ID	σ, (MPa)	Grinding time, (h) 1	2	4	8	16	Average wear rates of the balls, (%)
			Wear rates of the balls, (%)					
Mahd Ad Dhahab	Md-1	255	0.117	0.145	0.183	0.254	0.388	0.217
Al Amar	Am-2	261	0.113	0.132	0.169	0.248	0.372	0.207
Ad Duwayhi	Ad-5	254	0.119	0.148	0.187	0.256	0.392	0.220
Bulghah	Bu-5	255	0.125	0.161	0.203	0.258	0.405	0.230
Sukhaybarat	Suk-5	257	0.136	0.184	0.238	0.291	0.427	0.255
Mansourah-Massarah	MM-5	263	0.132	0.174	0.232	0.279	0.412	0.246

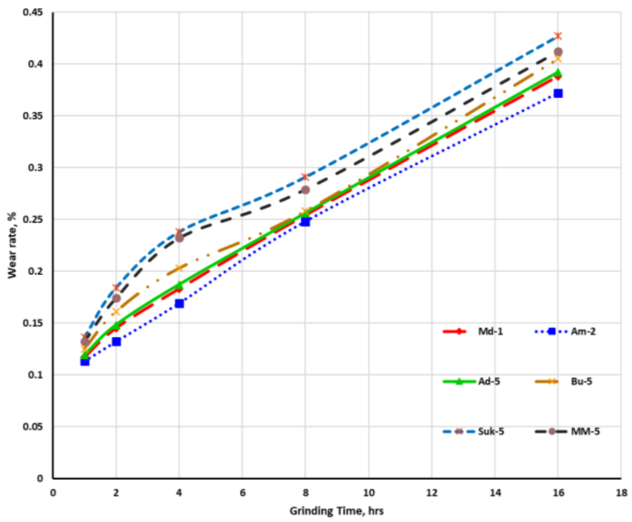


Figure 8. Wear rates of the balls in terms of different samples from six different mines with the same mechanical properties

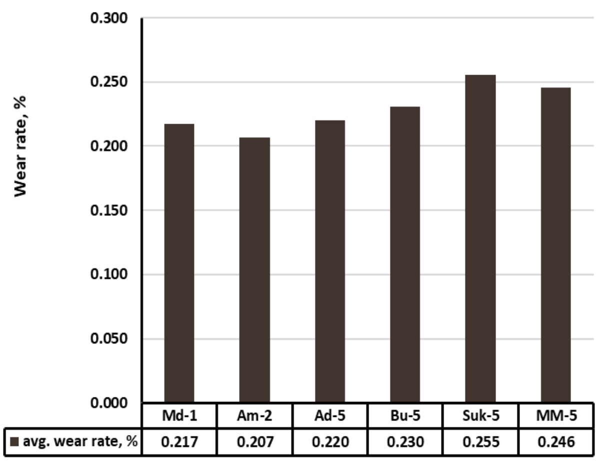


Figure 9. Average wear rates of the balls in terms of different samples from six different mines

By taking the average of the wear rates of each sample during different grinding time, sample Suk-5 gave the highest rate (0.255%), while sample Am-2 gave the lowest wear rate (0.207%) (Fig. 9). Since the wear values are close and range from 0.207 to 0.255, the result of the Sukhaybarat mine sample was used as a reference. Thus, the rest of the samples from other mines were compared with it so that the percentage of decrease in wear rates could be known (Fig. 10).

According to Figure 10, there are varying decreases in wear rates despite the approximate equality in the compressive strength values of these samples.

By comparing the MM-5, Bu-5, Ad-5, Md-1, and Am-2 samples with the Suk-5 one at a grinding time of 1 hour, the results gave a decrease in the wear rate values of 3, 8, 13, 14, and 17%, respectively. During all the analyzed grinding periods of time (1, 2, 4, 8, and 16 hours), those aforementioned samples, showed varying rates of decrease to compare with the samples of Sukhaybart Mine (Suk-5). In addition, the highest percentage of decrease in the wear value was observed in the Am-2 sample during the grinding time, being 4 and 2 hours; it was 29 and 28%, respectively.

The average decreasing % in wear occurring in the grinding balls during different grinding time were 4, 10, 15, 16, and 20% for the MM-5, Bu-5, Ad-5, Md-1, and Am-2 samples, respectively, compared with the Suk-5 sample as shown in Figure 11.

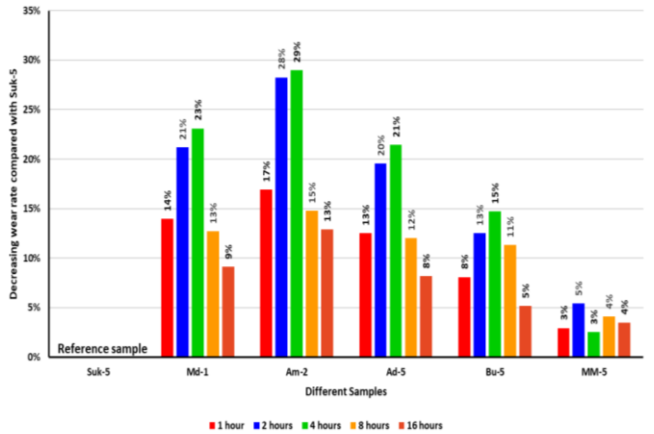


Figure 10. Decreasing % of wear rates of the balls in terms of different samples compared with Suk-5

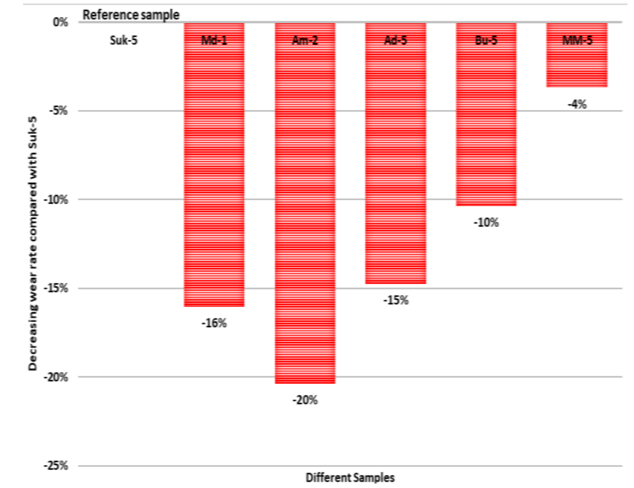


Figure 11. Average decreasing % of wear rates of the balls in terms of different samples compared with Suk-5

Therefore, it was necessary to think about the reason behind the increasing wear rates in the Suk-5 sample despite close convergence in values of the compressive strength of those rocks. Thus, powder samples were taken from the milling products, and thin sections were prepared to be studied under the microscope to know the petrographic properties.

3.3.2. Results of petrographic description

The petrographic descriptions showed the presence of a group of minerals prevalent in the rocks of each site. Further, the petrographic description will be reviewed successively in the context of six samples, bearing in mind that the description will be descending starting with the largest sample that caused balls wear (Suk-5) and ending with the lowest sample (Am-2).

Petrographic description of Suk-5 showed a small euhedral cube of disseminated pyrite (Py) associated with chalcopyrite (Ccp) aggregates (brass-yellow) embedded within quartz of a sulphide-rich quartz vein (Fig. 12). The paragenetic sequence indicated clearly that pyrite was formed first; later, chalcopyrite-rich fluids come to fill the cracks and cement the pre-existing pyrite grains. Figure 12 demonstrated clearly that the minerals asso-ciated with quartz were pyrite and chalcopyrite. Since their hardness range from 6.0 to 6.5 and 3.5 to 4.0 [26], [27] respectively, their combination with quartz caused greater wear rate than the rest of the samples.

In case of MM-5, which gave slightly lower wear rates than Suk-5, the microscopic images showed the presence of anhedral chalcopyrite (Ccp) grains (brass-yellow) replaced by chalcocite (Cc) along rims (grey); it is shown in Figure 13a.

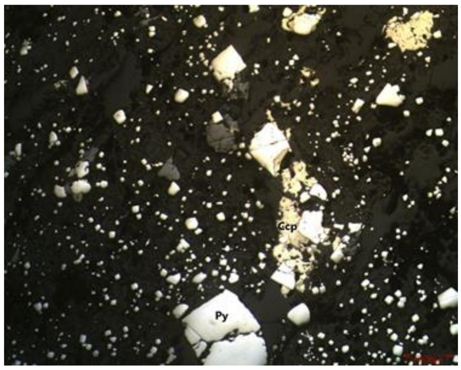
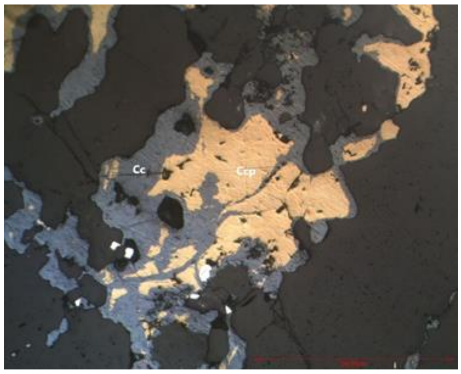


Figure 12. Petrographic description of Suk-5

(a)



(b)

Figure 13. Petrographic description of MM-5

It can be observed from the presence of small relicts of chalcopyrite within chalcocite as a replacement feature. Thus, chalcopyrite and chalcocite are both hosted by quartz (black).

Figure 13b shows a large cracked anhedral chalcopyrite (Ccp) mass (brass-yellow) replaced by chalcocite (Cc) along cracks (grey) within chalcopyrite. Both chalcopyrite and chalcocite are hosted by quartz in sulphide-rich quartz veins. Consequently, the minerals associated with quartz in this sample (MM-5) are chalcocite with a hardness of (2.5-3.0) and chalcopyrite with a hardness of (3.5-4.0) [26], [27]; it gave an average wear rate value of 0.207% which is less than Suk-5. The reason for this may be the fact that the latter contains pyrite, which has a higher hardness than chalcocite. This contributes to greater ball wear during milling operation.

As for the Bu-5 sample, which was in the third order in terms of causing wear of balls (0.230%), its petrographic description showed that it resembles the MM-5 sample in the presence of anhedral chalcopyrite (Ccp) grains (yellow) (Fig. 14); it differs in the fact that covellite (Cv) (blue) is found as a secondary mineral after chalcopyrite. Thus, the dominant minerals in Bu-5 are chalcopyrite and covellite; they are hosted by quartz (black) in a sulphide-rich quartz vein (Fig. 14).

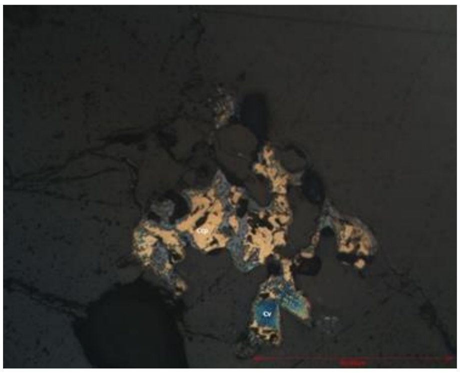
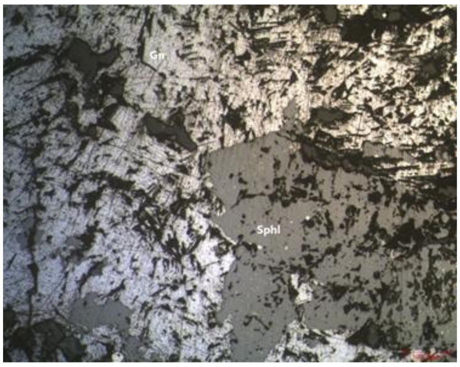


Figure 14. Petrographic description of Bu-5

Despite the presence of covellite with hardness (1.5-2.0), the percentage of quartz here occupies a reasonable space in the microscopic image, and it may be the reason behind this sample coming in the third order in causing wear of grinding balls. Petrographic description of Ad-5 (4^{th} sample with the average wear rate of 0.220%) reveals that large anhedral sphalerite (Sphl) grains (dark grey) are associated with brecciated galena (Gn) with characteristic triangular pits (Fig. 15a) whereas anhedral sphalerite (Sphl) grains (pale grey) with numerous small chalcopyrite (Ccp) exsolution lamellae (Fig. 15b).

(a)



(b)

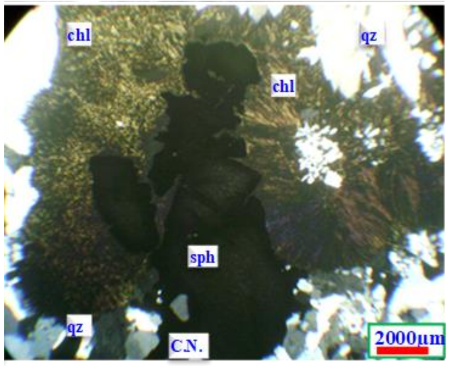
Figure 15. Petrographic description of Ad-5

This texture is called "chalcopyrite disease" [45], where small chalcopyrite needles or blebs exsolved from sphalerite during cooling of the mineralizing fluids. Sphalerite host and chalcopyrite aggregates are hosted by quartz (dark grey) of a sulphide-rich quartz vein.

Despite the existence of galena with low hardness (2.0-2.75), the ratio of quartz here occupies a large space, in addition to the association of sphalerite and chalcopyrite with hardness (3.5-4.0); they may be the main reason why this sample is ranked fourth.

With regard to Md-1 sample, which is the fifth occupying the penultimate place, Figure 16a, b shows distinctly that euhedral to subhedral sphalerite (Sph) grains are associated with chlorite (chl) and quartz (Qz).

(a)



(b)

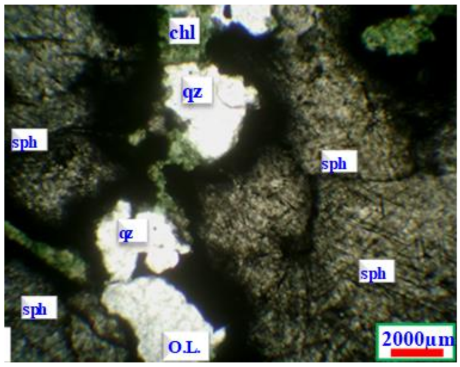


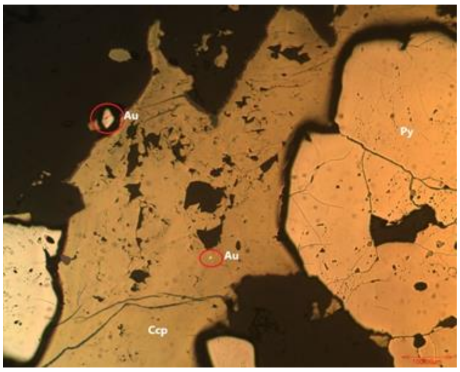
Figure 16. Petrographic description of Md-1

Chalcopyrite is one of the main sulphide minerals in Mahd Ad Dhahab gold mine that is found in many forms: as large aggregates, small needles, and blebs within sphalerite as well as disseminated grains in quartz veins. Chalcopyrite is brittle and dense (density = 4.1-4.3 $g.cm^{-3}$), and its hardness varies between 3½-4.0 on the Mohs scale. Sphalerite is also brittle and dense (its density is 3.9-4.1 $g.cm^{-3}$); its hardness varies between 3½-4.0 on the Mohs scale. However, the chlorite hardness ranges between (2.0-2.5), and it is probably the reason for the low wear rate because, according to the microscopic image (Fig. 16), it occupies the majority of the image. Notwithstanding the association of sphalerite, chalcopyrite, and quartz, the presence of chlorite in the sample may weaken relatively its effect on grinding balls wear.

Finally, the 6^{th} sample is Am-2, which has an average wear rate of 0.207%. The petrographic description of this sample shows that large euhedral cracked pyrite (Py) grains cemented by chalcopyrite (Ccp) are found as crack filling and cement materials. In addition, small gold (Au) grains are also found included within chalcopyrite and outside the matrix (Fig. 17a) while euhedral cracked pyrite (Py) grains and sphalerite (Sphl) (dark grey) cemented by galena (Gn) appeared in Fig. 17b.

Galena represents the latest phase in this association since it is found as crack-filling and cementing materials of the pre-existing pyrite and sphalerite. There is no quartz in this sample; perhaps, it is the reason that made it the last sample in the order in terms of causing wear of the mill balls.

(a)



(b)

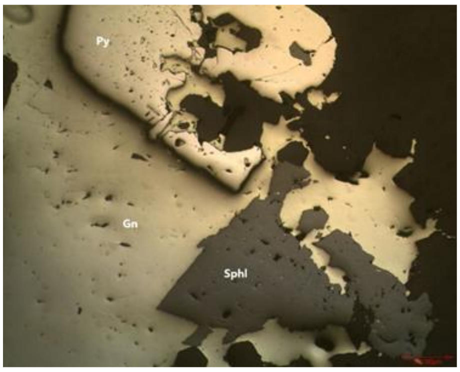


Figure 17. Petrographic description of Am-2

4. Conclusions

Basing on different mechanical properties (σ, E, and v) of 30 specimens, hardness classifications were developed. Most of the samples were classified as either extremely hard or very hard, while a few limited samples fell into the "hard" classification group, σ is less than 100 MPa. The ball wear rates, caused only by the Sukhaybarat rock samples (5 samples (Suk-1 to Suk-5) with different mechanical properties (σ, E, and v), were studied in case of dry milling and altered grinding time. It can be concluded that the higher the sample compressive strength is, the higher the ball rate is; and the greater the grinding time is, the greater the ball grinding rate is. There is a strong linear relationship between the wear rate of balls, on the one hand, and the applied grinding time and compressive strength, on the other hand. However, increasing grinding time has a greater effect than the effect of growing compressive strength.

Then six samples from different mines (Mahd Ad Dhahab, Al Amar, Ad Duwayhi, Bulghah, Sukhaybarat, and Mansourah Massarah) with approximately the same mechanical properties (σ, E, and v) were milled under the same milling conditions to observe the grinding ball wear rates and indicate possible differences. The results revealed that there is a discrepancy in the wear rate values among the six samples despite the equal values of their compressive strength. The Sukhaybarat Mine sample (Suk-5) gave the highest rate of wear (0.255%), in terms of different grinding time. Then it was followed by the samples of Mansourah Massarah (MM-5), Bulghah (Bu-5), Ad Duwayhi (Ad-5), and Mahd Ad Dhahab (Md-1); Al Amar (Am-2) gave the lowest wear rate (0.207%). By comparing the MM-5, Bu-5, Ad-5, Md-1, and Am-2 samples with Suk-5 at a grinding time of 1 hour, the results gave a decrease in the wear rate values of 3, 8, 13, 14, and 17%, respectively. Therefore, powder samples were taken from the milling products, and thin sections were prepared to be studied with the help of microscope to specify the petrographic description.

The petrographic descriptions showed the presence of a group of minerals prevalent in the rocks of each site. Petrographic description of Suk-5 showed that pyrite (Py) is associated with chalcopyrite (Ccp) aggregates embedded within quartz of a sulphide-rich quartz vein. The associated minerals with quartz have high hardness, and their combination with quartz caused greater wear rate than the rest of the samples. At the same time, the petrographic descriptions of Am-2 sample, which has the last average wear rate, showed that pyrite (Py) grains are cemented by chalcopyrite (Ccp) and galena (Gn). In this sample, quartz did not appear, and perhaps this is the reason that made it the last sample in the order in terms of causing wear of the mill balls. Thus, it can be stated that despite the equal compressive strength of these six samples, the association of some minerals (e.g. pyrite) with quartz gives a countervailing effect that increases their hardness and, accordingly, causes the increasing wear rates of balls.

Acknowledgments

This project was funded by the Deanship of Scientific Research (DSR), at King Abdulaziz University, Jeddah, under grant No. G: 797-135-1441. The authors, therefore, acknowledge with thanks to DSR for technical and financial support.

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Вплив неоднорідності руди на швидкість зношування кульової подрібнювальної установки в процесі подрібнення на золотих рудниках Саудівської Аравії (Королівство Саудівська Аравія)

Г.С. Абдельхафез, Х.М. Ахмед, Х.А. Салім

Мета. Вивчення впливу процесу подрібнення золотовмісних руд на швидкість зношування подрібнювальних кульок на золотих рудниках Саудівської Аравії.

Методика. З окремих шахт Королівства Саудівської Аравії було відібрано шість зразків валунної породи, і з кожного відібрано по 5 зразків керна для визначення механічних властивостей (міцність на стиск, модуль Юнга та коефіцієнт Пуассона). Ці механічні властивості були повторно використані для класифікації класу твердості всіх 30 зразків керна. П’ять зразків з різними механічними властивостями з одного і того ж зразка валуна було подрібнено для вивчення впливу різниці міцності на стиск та часу подрібнення на швидкість зношування. Потім із різних регіонів було відібрано шість зразків зі схожими механічними властивостями, але відмінними за петрографічними характеристиками. Їх також подрібнювали в тих самих умовах подрібнення для вивчення впливу мікроскопічного складу мінералів на швидкість зношування.

Результати. Встановлено, що швидкість зношування збільшується з покращенням механічних властивостей, а також зі збільшенням часу подрібнення. З іншого боку, результати, засновані на різних мікроскопічних описах шести зразків, продемонстрували, що, незважаючи на подібні механічні властивості, швидкість зношування відрізнялася. Визначено, що петрографічна характеристика підтвердила присутність кварцу в більшості зразків як супутнього мінералу, і, ймовірно, він має найбільший вплив на зношування подрібнювальних куль.

Наукова новизна. У цій статті пропонується метод дослідження неоднорідності руди, що значно впливає на швидкість зношування в процесі подрібнення, а також на зниження витрат і підвищення ефективності подрібнювальних тіл.

Практична значимість. У цьому дослідженні наголошується на важливості вивчення змінних (наприклад, неоднорідності руди), окрім розміру куль, складу подрібнювальних тіл, мокрого або сухого подрібнення, що мають істотний вплив на ефективність подрібнення. Отримані дані можуть бути застосовані в техніко-економічних обґрунтуваннях для розрахунку та оцінки витрат на подрібнення у порівнянні з ефективністю подрібнення.

Ключові слова: *шахти з видобутку золота Саудівської Аравії, твердість золотої породи, механічні властивості, петрографічні описи, швидкість зношування, кульова подрібнювальна установка*