Influence of geometric design variables on the efficiency of the high energy horizontal chromite type ball milling process

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Elemental chromium (Cr) does not occur in nature, but Cr exists in chromite ores as $FeOCr_2O_3$. There are some processes to obtain Cr from chromite. For all processes milling process is essential. In milling process of chromite, ball mills are generally used, because follow-up processes need fine particle size. Due to the fact that chromites with a high iron content are hard, mill components like liner and grinding media wear faster than many mines which is a significant problem in chromite grinding. This paper presents an experimental investigation of the influence of liner profile design and speed on chromite ball milling process. For evaluation of the experiments, power consumption, particle size and wear rate datas are calculated. In this experimental study, five liner profiles were designed and worked with three speeds (60, 70 and 80 % critical speed). By this combination, this study contains fifteen experiments. The ball milling process efficiency is related with shape of grinding media, kind of grinding media and product filling degree, ball size distrubition, etc., all other factors are kept constant. It was investigated the effects of liner profiles-milling speed variations on milling efficiency. 70 % critical speed was the optimum speed for all liner types. Best particle size result was meausured in the 10^{th} experiment as 95 μm which has the highest liner. Also, the steepest liner profile has the second-best result at a critical speed of 70 %. Energy saving is important for selecting liner profile. Besides, shallowest design with 80 % critical speed has the worst particle size result. Although highest liner profile Type 5 has the best result for particle size, the difference of wear rates is nearly two times (160 g versus 90 g) compared to Type 3 which has a particle size result of 100 μm. This means nearly half life time difference between two liners. By considering three parameters, power consumption, particle size and wear rate, the best results occurred with the steepest and medium liner profile, and these may even be further improved.

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Keywords
Chromite ore, ball milling, design, liner, media

Chromium is one of the most important elements for industry., but it cannot exist in elemental form in nature. Chromite ($FeOCr_2O_3$) ores are sources for chromium element. For seperating chromium from ores, there are known some processes including mining, crushing, milling, kilning, etc. [1, 2].

Generally, chromite milling is performed in ball mills before feeding pre-heating and after rotary kiln for obtaining chromium compounds. Ball mills are generally used for fine grinding operations. Liners are one the most important component of ball mills. They have important effects on ball milling process.

Parks and Kjos [3] described that the prime duty of liners is protecting the mill shell, other important functions are transmitting energy to the mill load and lifting up the grinding media. Thus, they have a key role in tumbling mills performance. Wills and Napier-Munn [4] specified mill shell liners to have different lifters profiles resulting in different effects on the grinding mechanism. Makokha et al. [5] indicated that liners have huge impact in the milling process due to their strong influence on load motion and behavior.

Generally, motion of the load (grinded material and grinding media) determines the efficiency of the milling process, which governs the nature of the ore presented to the grinding media, the mode of breakage and subsequent transport. It is should be considered that a mounted liner will lose efficiency due to wear. The liner height and leading angle will normally decrease and thus be less able to project the balls with high kinetic energy. Therefore, most of the researchers focused on liner design for many years. The mill power consumption is influenced by a range of parameters such as charge and slurry filling, number and geometry of lifters and mill speed. Providing optimum parameter values should let mill work efficiently.

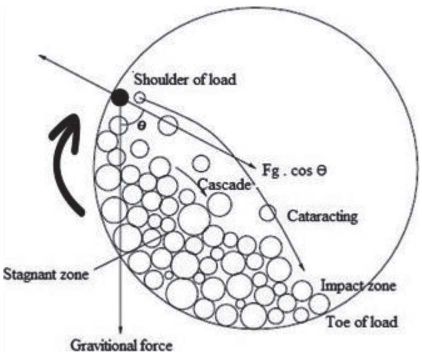

Figure 1: Ball motions in a ball mill

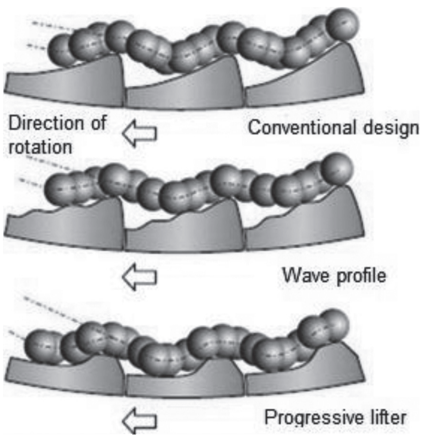

Figure 2: Ball trajectories according to the liners designs [7]

In the ball mill process, there are two important ball motions. One of this is cataract motion which provides rough (primer) grinding with impact force. The second is cascade motion which provides fine grinding with friction force. In Figure 1, ball motions in a ball mill are shown.

McIvor [6] reported the effects of liner design charge motion in ball mill. In his study, it was defined that the outer layer of the charge consumes a significant portion of the total input of power to the mill, and is also responsible for transfer of energy to the bulk of charge. It was also concluded that the outer layer of charge has a significant effect on the motion of the bulk of the charge. It was concluded that the trajectories of the particles are highly sensitive to leading face angle of the lifter bar. Although it was not releaved in the calculations, it was observed that the height of the lifter bar affects the trajectories. In Figure 2, it is shown the ball motion in a ball mill according to different types of liners. As it can be seen, shapes of liners cause different trajectories which affect cataracting and cascading and therefore milling performance.

Also, McIvor [6], Powell and Nurick [7] studied shell liner design by combination with various combinations of lifter heights, spacing and angles. Changing the face angles affects grinding ball trajectories, and hence, the point of impact within the mill, and the spacing between shell lifters affects charge lifting rate, and hence mill performance.

Vermeulen [8] recognized that the width of the bar affects the angle of its leading face and, most importantly, that the particle is not projected into the air from the base of the bar. He defined motion of the ball with the equation of force. It is evident that the particle remains in contact with the lifter bar, and rolls or slides down the face until it reaches the tip of the bar where it is projected into flight. This situation shows the way in which the height of the lifter bar affects the degree of lift of the particles.

Because of strong impacts and friction force, components of ball mill wear after certain working hours. So, there are changeable covering liner plates. As these liners wear the surfaces interacting with the particles commonly change shape leading to changes in the particle flows, charge pressures, shear rates, particle breakage, material transport, power consumption and therefore the operational performance. Therefore, the performance of a comminution device can change dynamically and strongly throughout the life cycle of the liner. The changing particle flow also leads to changes in the wear patterns on the liner which then feeds back into the shape evolution of the liner [9].

Toe and shoulder angles of the charge are always used for liner design purpose. Clermort et al. [10] indicated importance of this subject. The risk of liner and ball damage by projecting balls directly onto the shell liner should be avoided. Hence, a good liner design and correct operating conditions such as mill speed or balls filling degree should limit the risk of projection. In his experimental study, Lameck [11] proved that cataracting is normally achieved by increased mill speed and/or changing the liner/lifter profile. However, this could result in an increase in grinding media impact onto mill shell/liners.

In chromite ore grinding process, grinding occurs more in cascade motion than cataract motion. Therefore, grinding of chromite is an abrasive application. Abrasion occurs within the bulk (chromite ore), grinding media and liners. So, an appropriate liner design should be achieved for grinding chromite ore. In literature, studies do not include specific ore grinding as chromite.

In this paper, we studied on effect of liner profile and mill speed on chromite ball milling process. An experimental scaled ball mill was manufactured for this study. Provided that all other grinding media are constant, liner dimensions and mill speeds were variable. Other researchers focused on relation between power consumption and wear rates. In this study, we focused on specific power consumption and product size relation by regarding wear rates for chromite. Specific power consumption and product size were measured for each experiment, and by comparing these values, effects were determined.

Theoretical background

The details of the experimental ball mill are given in Table 1.

The ball size in a mill has a significant influence on the mill throughput, power consumption and ground material size [12]. So, it is important to detect ball diameters. For appointing the ball diameter range, first, it is important to calculate and determine maximum points.

Figure 3: Snapshots from manufacturing steps of experiment grinding media

Cleary [13] studied the ball filling degree on milling performance and this study shows that filling degrees between 10 to 50 % linearly increases power consumption at the rate of 60-80 % at critical speeds. In his study, the experimental results show that 25 % filling degree is the intercept. At higher values, power consumption increases proportionally with speed. Another study by Powell et al. [14] accepted standard mill operating conditions with 25 % filling for ball mills Therefore, in our study, we selected filling degree of 25 % which equals to a weight of 253 kg.

Experimental materials and procedures

For experiments, we used a ball mill with shell dimensions of 550 mm inner diameter and 1330 mm length. Figure 3 shows manufacturing steps of experimental ball mill. Drive system was designed as pinion gear system. Feeding system was designed as batch working. Liner dimensions defined for 4 rows in ball mill and 8 liners for each row. In total, 32 liner plates were mounted in ball mill. As it can be seen in Figure 4, 5 types of liners operated with 3 different mill speeds. By this combination, study included 15 experiments. Figure 4 shows manufacturing details of 5 types of liners.

Many designs of shell lifters have been used over the years [15, 4]. Royston [16] defined that current shell lifter designs commonly adopt large face angles, typically 22° but up to 35° with high shell lifters, to provide ball impact at the toe of the charge with spacing between lifters, sufficient to overcome packing. Cleary [13] experimented with 80 % critical speed (comparatively) and identifed that when the lifter has been reduced to a 22.5° face angle, there is almost no cataracting material at all and it barely moves beyond the avalanching surface of the charge. Liners were designed by considering this information. But also 50° face angle was performed. Details of experiments as numbered can be seen in Table 2.

A pre-study was carried out for defining experiment duration. According to this pre-study, mill was operated for 30 minutes and afterwards particle size analysis was performed. Then, mill was operated for another 30 minutes and analysis was made again. After 180 minutes, particle analysis showed that there was no change. Therefore, experiment duration was defined as 180 minutes.

Results and discussion

The results are given in Table 3. Also, in Figure 5, combi-graphics was given for product size and power consumption for each experi-

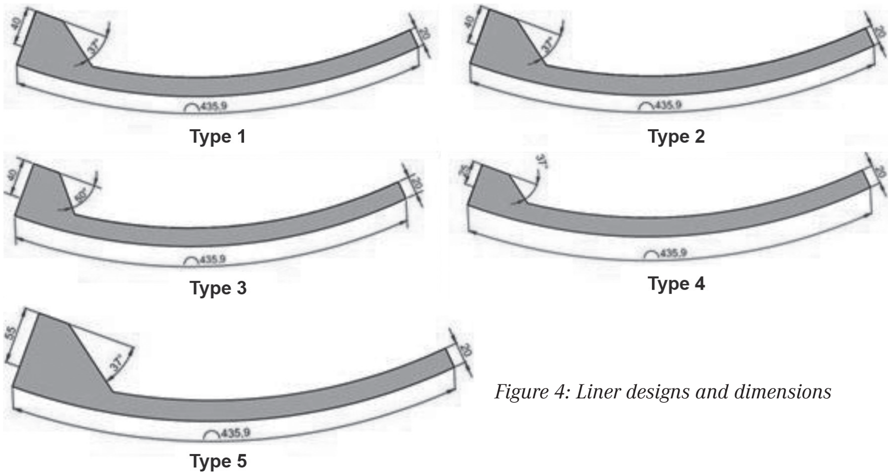

Figure 4: Liner designs and dimensions

Mill	Inner diameter D (mm)	555	calculated from $Nc = \frac{42.3}{\sqrt{Dm}}$
	Length (mm)	1300	
	Volume (dm³)	314.34	
	Critical speed Nc (rpm)	57.3	
Media (balls)	Material	Alloy steel	calculated from $Dmax = 20.17 \cdot \sqrt{\frac{D20}{K}} \cdot 3 \cdot \sqrt{\frac{Wi \cdot \varphi}{Nc \cdot \sqrt{Du}}}$
	Diameter range d (mm)	10-20 (max. 20)	
	Specific gravity	7.85	
	Filling ratio (%)	25	
	Filling weight (kg)	253	
Grind material	Material	Chromite ore	calculated from $Q = \left(\frac{\pi \cdot Du^2}{4}\right) \cdot L \cdot d \cdot Vp$
	Specific gravity (kg × m⁻³)	4500	
	Humidity (%)	1	
	Maximum particle size (mm)	1.1	

Table 1: Experimental information of the ball mill

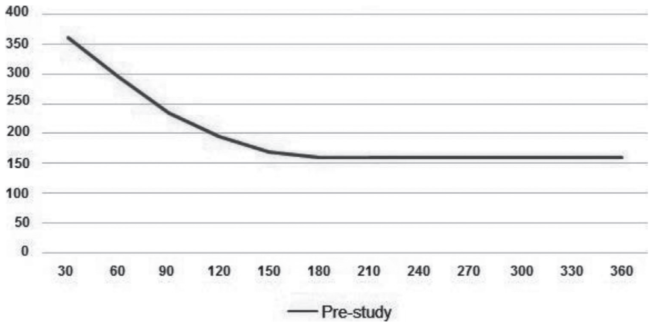

Figure 5: Test details of pre-study

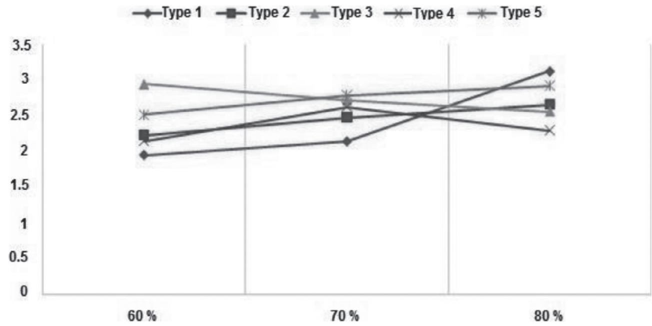

Figure 6: Milling speed-power consumption relationship

ment. As can be seen, minimum particle size of 95 µm occurred in the 10th experiment using Type 5 liner and 70 % critical speed. In this experiment, the specific power consumption was 2.79 kWh. The maximum particle size of 205 µm occurred in the 14th experiment using Type 4 liner and 80 % critical speed. In this experiment, the specific power consumption was 2.29 kWh.

Evaluation result by milling speed. In Figure 6, it is shown the speed and power consumption results in graphics. Detailed evaluation by liner types reveals:

- 60 % critical speed: A comparison of the 1st, 2nd and 3rd experiments with the same lifter height shows that the specific power consumption increases by face angle raise. This observation supports Cleary's [13] determination that the highest power draw occurs at low speeds. Also, the analysis shows that particle sizes are decreasing. A comparison of the 4th, 2nd and 5th experiments having the same face angle shows that the specific power consumption increases by liner height raise. But analysis results indicate that lifter heights of 25 mm and 40 mm provide same particle size of 55 mm.
- 70 % critical speed: A comparison of the 6th, 7th and 8th experiments also having the same lifter height shows that the specific power consumption increases by face angle raise as in the experiments with 60 % critical speed. Also, particle size analysis results provide same cases as experiments with 60 % critical speed. A comparison of the 9th, 7th and 10th experiments having the same face angle shows that the specific energy consumption does not follow the same trend as the experiments with 60 % critical speed. A height of 25 mm provides more specific power consumption than a height of 40 mm, whereas a height of 55 mm provides the most power consumption.
- 80 % critical speed: A comparison of the 11th, 12th and 13th experiments having the same lifter height shows that the specific power consumption decreases by face angle raise. This behavior has the opposite trend of the experiments with 60 % and 70 % critical speed. A comparison of the 14th, 12th and 15th experiments having the same face angle shows that lifter height raise and particles size are not directly proportional. At this speed, 25 mm lifter height provides the worst particle size in all 15 experiments. 40 mm lifter height provides better particle size results than 55 mm lifter height. But it can be seen that a raise of lifter height also increases the specific power consumption as seen in the experiments with 60 % and 70 % critical speed [17].

Experiment number	Liner type	Liner properties	Speed
1	Type 1	Height: 40 mm, Angle: 20°	34 rpm, 60 % C. S.
2	Type 2	Height: 40 mm, Angle: 37°	34 rpm, 60 % C. S.
3	Type 3	Height: 40 mm, Angle: 50°	34 rpm, 60 % C. S.
4	Type 4	Height: 25 mm, Angle: 37°	34 rpm, 60 % C. S.
5	Type 5	Height: 55 mm, Angle: 37°	34 rpm, 60 % C. S.
6	Type 1	Height: 40 mm, Angle: 20°	40 rpm, 70 % C. S.
7	Type 2	Height: 40 mm, Angle: 37°	40 rpm, 70 % C. S.
8	Type 3	Height: 40 mm, Angle: 50°	40 rpm, 70 % C. S.
9	Type 4	Height: 25 mm, Angle: 37°	40 rpm, 70 % C. S.
10	Type 5	Height: 55 mm, Angle: 37°	40 rpm, 70 % C. S.
11	Type 1	Height: 40 mm, Angle: 20°	46 rpm, 80 % C. S.
12	Type 2	Height: 40 mm, Angle: 37°	46 rpm, 80 % C. S.
13	Type 3	Height: 40 mm, Angle: 50°	46 rpm, 80 % C. S.
14	Type 4	Height: 25 mm, Angle: 37°	46 rpm, 80 % C. S.
15	Type 5	Height: 55 mm, Angle: 37°	46 rpm, 80 % C. S.

Table 2: Details of experiments

Evaluation results by liner profile

The following results were revealed regarding liner profile, as can be seen in Figure 7:

	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8	Exp. 9	Exp. 10	Exp. 11	Exp. 12	Exp. 13	Exp. 14	Exp. 15
Particle size(µm)	160	150	135	150	130	140	120	100	125	95	155	135	150	205	150
Power consumption (kW)	1.95	2.23	2.94	2.15	2.52	2.14	2.48	2.72	2.62	2.79	3.12	2.66	2.56	2.29	2.92
Wear rate (g)	90	110	80	70	140	120	130	90	80	160	150	140	110	100	190

Table 3: Product size and power consumption for each experiment

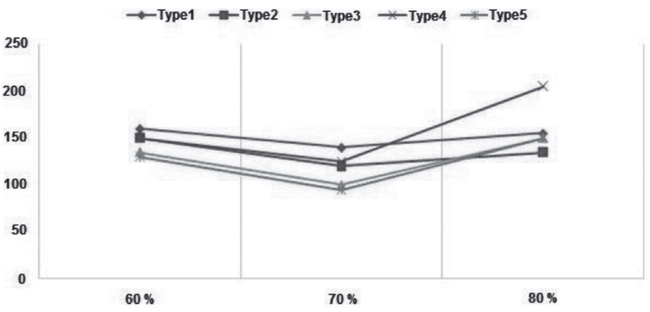

Figure 7: Milling speed-particle size relationship

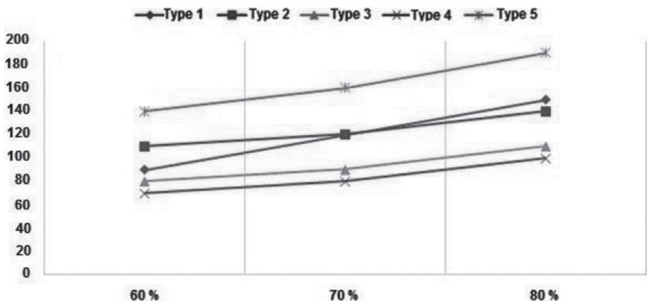

Figure 8: Wear rates for liners

- Type 1: Best particle size was measured at 70 % critical speed At 60 % and 80 % critical speed, particle size values were nearly the same namely 160 µm and 155 µm. But specific power consumption dramatically increased from 1.95 kWh to 3.12 kWh. This is the biggest difference of power consumption between the same liner with three different speeds. Specific power consumption increased by speed raise.
- Type 2: Best particle size and minimum specific power consumption was measured at 70 % critical speed, so this speed is the most efficient value for this liner profile. Specific power consumption increased by speed raise.
- Type 3: Best particle size was measured at 70 % critical speed. Also, this value is the second-best value of all experiments. In this liner profile, specific power consumption decreased by speed raise which is the opposite trend compared to Type 1 and Type 2 liner profiles. This is the steepest liner profile and these results also support experiment results [13].
- Type 4: Best particle size was meausured at 70 % critical speed. Whereas, worst particle size was meausured at 80 % critical speed. Nevertheless, minimum power consumption occurred at 80 % critical speed. This is also the worst particle size result of all 15 experiments. This liner profile has minimum lifter height. This shows that lower liner profiles have a negative impact on particle size. Specific power consumption does not show a direct trend by speed raise.
- Type 5: Best particle size was measured at 70 % critical speed and this is also the best particle size of all experiments. Specific power consumption increased by speed raise.

Evaluation results by liner wear rates. As seen from Figure 8, minimum wear rate occurred using Type 4 liners, whereas maximum wear rate occurred using Type 5 liners. Considering Type 4 as the lowest and Type 5 as the highest liner, showed the highest wear rate. Results also show that wear rates increased with speed increase.

By considering all 15 experiments, minimum specific power consumption has occurred in the 1st experiment and maximum specific power consumption has occurred in the 11th experiment having the same liner profile, Type 1. This demonstrates that same liner design may cause minimum and maximum power consumption by speed variation. In four experiments (Experiments 2nd, 4th, 13th and 15th), particle size analysis results revealed the same value as 150 µm. The 2nd and 4th experiments ran with 60 % critical speed. Also, the 13th and 15th experiments ran with 80 % critical speed. In this experiment group, all experiments have different liner profile and the most efficiently one is the 4th experiment, because of its minimum power consumption. As demonstrated, extra power input obtained by increasing speed does not have any effect and does not result in a finer grinding degree [18].

Conclusions

Although there is an optimum liner profile for every process, experiments show that each liner profile has an optimum speed. That means optimum milling efficiency can be achieved by optimizing liner profile with right milling speed. A milling process with a constant liner design can also be optimized by speed variation. In this study, for all types of liners, optimum speed occured at 70 % critical speed.

It can be calculated from test results that the avarage particle size is 140 µm and the avarage specific power consumption is 2.54 kWh. Because of production continuity, particle size is more important than power consumption. Most efficient milling process is with suitable particle size with mininum power consumption. In these experiments, the best particle size was measured in the 10th experiment with 95 µm. The next best value is 100 µm in the 8th experiment. But it must be considered that wear rates are 160 g and 90 g, respectively. That means that the life time of Type 3 liner is nearly two times higher than for Type 5 liner. In this case, it is highly important to determine process output for companies. The power consumption of Type 3 liner is 2.50 % less than Type 5 liner, whereas particle size is higher than with Type 5. In chromium recovery process, a variation of particle size of ± 5 % is acceptable for subsequent processes. The steepest liner (Type 3) shows the best liner profile. This liner could be used for further studies on the effects of steeper angles and different heights. This study may lead to associated studies for determining specific liner design formulas.

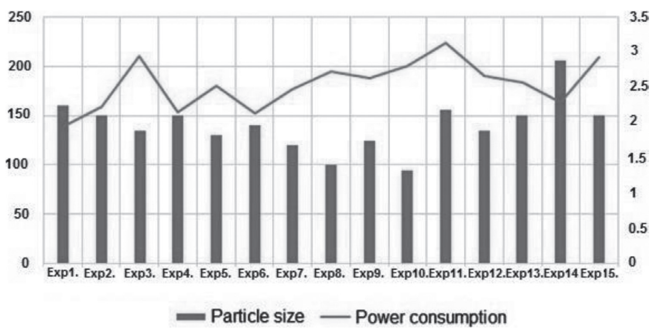

Figure 9: Results of experiments in combigraphics

Acknowledgments

The authors would like to thank Sisecam Chemicals Group Soda Sanayii A.S. in Mersin, Turkey for their support of this study. Special appreciation is also expressed to maintenance personnel who helped to prepare experiments.

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Abstract

Einfluss der geometrischen Designvariablen auf die Effizienz des Hochenergie-Kugelmahlprozesses für Chromit. Elementares Chrom (Cr) kommt in der Natur nicht vor, es existiert nur in Verbindungen, z. B. als chromithaltige Erze wie $FeOCr_2O_3$. Es gibt einige Prozesse, um Chrom aus Chromiten zu erhalten, wobei für alle Gewinnungsmethoden ein wichtiger Prozessschritt das Mahlen ist. Im Mahlprozess des Chromits werden üblicherweise Kugelmühlen verwendet, da die nachfolgenden Prozesse sehr feine Partikel erfordern. Da hocheisenhaltige Chromite hart sind, verschleißen die Mühlenkomponenten und die Mahlkörper schneller als viele andere, was eine besondere Schwierigkeit beim Chromitschleifen darstellt. Im vorliegenden Beitrag wird eine experimentelle Untersuchung der Effekte des Linerprofildesigns und der Geschwindigkeit auf den Chromit-Kugelmahlprozess vorgestellt. Zur Evaluation der Experimente wurden die Daten des Energieverbrauches, der Partikelgröße und der Verschleißrate berechnet. In der experimentellen Studie wurden fünf Linerprofile entworfen und mit drei Geschwindigkeiten (60, 70 und 80 % der kritischen Geschwindigkeit) bearbeitet. In dieser Kombinationsstudie waren fünfzehn Experimente enthalten. Die Effizienz des Kugelmahlprozeseses wurde auch in Bezug zur Medienform, den Medien und dem Produktbefüllungsgrad, der Kugelgrößenverteilung, usw. gesetzt, wobei in dieser Studie alle anderen Faktoren konstant gehalten wurden. Außerdem wurden die Effekte der Linerprofil-Mahlgeschwindigkeits-Variationen auf die Mahleffizienz untersucht. 70 % der kritischen Geschwindigkeit war die optimale Geschwindigkeit für alle Linertypen. Die beste Partikelgröße wurde im zehnten Experiment mit 95 μm gemessen, in dem das höchste Linerprofil verwendet wurde. Außerdem ergab sich mit dem steilsten Linerprofil das zweitbeste Ergebnis bei 70 % der kritischen Geschwindigkeit. Aufgrund der Energieersparnis ist dieser Fall bedeutend für die Wahl des Linerprofils. Die flachste Auslegung mit 80 % der kritischen Geschwindigkeit ergab das schlechteste Resultat. Obwohl sich das Linerprofil Typ 5 hinsichlich der Partikelgröße als am besten erwies, ergaben sich fast zweifach höhrere Verschleißwerte (160 g gegenüber 90 g), im Vergleich zu dem nächsten Ergebnis für Typ 3, in dem sich eine Partikelgröße von 100 μm einstellte. Dies bedeutet eine Differenz für die Linertypen von nahezu der Hälfte. Unter Berücksichtigung der drei Parameter, Energieverbrauch, Partikelgröße und Verschleißrate, wurden die besten Resultate für das steilste und das mittlere Linerprofil erhalten, die zudem verbessert werden könnten.

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DOI 10.3139/120.111058
Materials Testing
59 (2017) 7-8, pages 689-695

ISSN 0025-5300

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