

The effect of high voltage electrical pulses on iron ore comminution to improve desulfurization flotation recovery

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Abstract: In this research, the effect of employing high voltage electrical pulse (HVEP) on crushing to improve the recovery of iron ore desulfurization was investigated compared to mechanical crushing. To determine the effect of mechanical and electrical crushing, jaw crusher, cone crusher, and high voltage electrical pulse crusher (50Kv) were applied. The results indicated that coarser particles with fewer slimes are produced in the initial crushing stage using electric pulses. Selective separation mechanism from the boundary of the particles based on different dielectric constants, was the main difference between the HVEP method and mechanical crushing. In the flotation process of sulfide minerals crushed by an electric pulse crusher, recovery of the sample was 10.6% higher, and the grade of sulfur in flotation residue of iron ore concentrate was approximately 58% lower than the sample which was undergone through the initial mechanical crushing stage. The obtained results evidenced 37.5% increase in flotation kinetics constant while electric pulse crushing is preferred to mechanical crushing. For mineralogical studies, microparticles (-38 microns) were studied in the pulp phase of the sample, and the results proved that in the electric pulse crushing of the microparticles, they are dispersed, and there is a distance between them, while in the mechanical approach they are formed in the shape of agglomerated particles. This phenomenon leads to better preparation and further possible contact of pyrite particles with air bubbles, which increases flotation kinetics and the recovery of sulfur merely when electric pulse crushing was employed.

Keywords: high voltage electrical pulses, crushing, flotation, desulfurization, iron ore

1. Introduction

In the last decades, due to the high consumption of iron ore in metallurgy industries, the demands for iron ore have been increasing (Saravari and Shayanfar, 2021). As the high-quality iron ores decrease over the years, impure iron-bearing minerals (e.g., sulfur as an impurity) have been considered for the further concentrating processes (Yu et al., 2013). High sulfur content in iron ore negatively impacts the quality and processing operation of the produced iron. The origin of sulfur in iron ore samples is usually Pyrite, Pyrrhotite, Chalcopyrite, etc. (Yu et al., 2016). Flotation was used as a separate commercial process to remove pyrite from iron-bearing minerals. Studies on reducing the amount of sulfur content from iron ores have been considered by many researchers worldwide (Mermillod-Blondin et al., 2005). In the separation process, flotation is generally accomplished after crushing, grinding, and other separation methods (Zhang et al., 2021). Over the years, lots of research have been carried out to improve the iron ore flotation process, reagents, and equipment, but less attention have been taken to adjust the crushing/grinding processes. The high Voltage Electrical Pulse (HVEP) method for crushing the ore samples has been investigated for many years. However, HVEP is not yet developed to reduce the competitive size compared to the traditional mechanical fracture. However, according to its capabilities in recent years, it widely noticed for downstream processes (Zuo et al., 2020).

The high voltage electric pulse is one of the methods which could be performed based on the application of tensile stresses in the crushing stage. Electrical breakdown is caused when a high voltage discharge is deposited within the plasma channel of an ore particle, and the solid's conductivity is not sufficient to allow the current to pass without atomic changes. The resistance or ionization potential is

too small to prevent the current from passing. The current moves through the ore particle in thin microplasma streamers, which branch out in a tree-like pattern to high electric field strength areas. Once the electrodes are bridged, the minerals in the particle continue to ionize and increase in temperature, causing an increase in conductivity and rapid expansion of the plasma stream. This phenomenon causes significant tensile stresses to form along the grain boundaries, leading to selective fragmentation. Electrostriction tension results when a polarised dielectric is exposed to an electric field. The dielectric deforms elastically in the applied field direction due to the different charges attracting and repelling. Electrostriction alone cannot cause selective fragmentation because ionization and electrical breakage are too rapid and do not allow time for the electrical field to reach a point where the stresses are sufficient to cause strictional mechanical disintegration. Strictional tension does, however, contribute toward the total mechanical stresses and generation of some fissures within the ore particle. So, the high voltage electric pulse can be served as an influential factor in energy consumption, achieving the appropriate liberation degree in coarser size fractions and less slime production (Andres, 2010; Yan et al., 2020).

A review of the records showed that since 1960, continuous and purposeful research had been conducted by various researchers. Anders was one of the leading researchers in energy pulses who studied the mechanisms of the mineral breakdown of high voltage pulses in detail and found that failure is mainly due to changes in the electrical charges of minerals. Electric pulse crushing takes place in an aqueous medium, and the main reason for the decomposition of minerals in an aqueous medium is that when the excitation time of the pulse is lower than 500 ns, the decomposition power of water is lower than that of solid minerals. In addition to energy consumption, Anders et al. studied the liberation of minerals from apatite-nepheline ores, kimberlite sample diamonds, ores containing platinum group metals, quartzites containing gold, and green emeralds from silicate ores which in electrical crushing clean and liberated minerals and crystals were obtained in comparison to mechanical crushing. Also, studies were performed on the recovery of platinum group metals from sulfide ores, gold from sulfide deposits, silver from manganese sulfides, magnesium from Willemite ores, and copper from low-grade sulfide ores, which resulted in increased recovery of electronically crushed samples compared to mechanical crushing. In addition, in the liberation of iron oxide ores (hematite and magnetite), some studies resulted in lower slime production and lower silica and phosphorus recovery in iron ore concentrate in the electrical crushing method than the mechanical one (Andres et al., 1999; Andres et al., 2001; Andres, 2010).

Also, Cabri et al. studied zircon, heavy minerals, gold, and platinum metals, which resulted in better liberation and increased cracks in electrical crushing compared to a mechanical one. Better liberation of emeralds and crystals of jewelry minerals and increased recovery of native gold were other results of their researches. In addition, they took steps to develop the device and compare electrical crushing methods (Cabri, 2004; Cabri et al., 2005; Cabri et al., 2008).

Wang et al. investigated the pre weakening of ores using high-voltage electrical pulses at low energy levels and its effect on reducing energy consumption in downstream milling processes. Microscopic studies showed many produced cracks in the electrical crushing method. In addition, energy consumption estimates for subsequent processes showed a 24% reduction in the preparation of samples by the electrical method. Also, the comparison between mechanical and electrical preparation for crushing using the same energy level showed that electrical preparation compared to mechanical preparation causes the production of coarser particles, lower slime, and an increase in liberation degree (Wang et al., 2011). In developing a method based on a single-particle failure test to investigate the effect of electrical pretreatment with high voltage pulses, the increase of cracks showed that energy consumption in autogenously and semi-autogenic mills could be decreased with electrical pretreatment or the input capacity to ball mill could be increased (Shi et al., 2013; Zuo et al., 2015). So, one advantage of HVEP is the creation of cracks/micro-cracks by electrical failure channel explosions that ultimately results in further energy-saving crushing/grinding processes.

Another proposed application of HVEP is as a pre-concentration step. In this technology, electrical pulses are discharged on ores with relatively low energy levels to separate the desired minerals from waste rocks. The feed of ores screening-based extraction is divided into high and low-grade products (Shi et al., 2014; Shi et al., 2015). In 2015, Zuo and Shi attempted to produce electric crushing and channel

formation results, pre-concentration of Cu ores, and fracture behavior on the semi-industrial scale (Zuo et al., 2015). Huang and Shi also discussed the fracture of multiple particles by employing high voltage pulses and concluded that ore particles could absorb more energy than waste particles. Simulation methods have also been applied to illuminate the effect of inorganic components and their shapes on electric field distribution (Huang and Shi, 2018). Yan et al.'s study on copper ore revealed that minerals with large dielectric constants are easily broken, which may be suitable for gravity separation (Yan et al., 2019).

According to the previous process studies, liberation degree, surface cleanliness, recovery increasing, pre-weakening due to produced cracks, and pre-concentration had been the most critical advantages of pulse electrical crushing compared to mechanical crushing. So far, only operating conditions and reagents have been considered in the investigation of the desulfurization of iron ore by flotation and the subject of crushing, especially the comparison of electrical and mechanical crushing, had not been considered. In the current research, the effect of electrical pulse crushing on the desulfurization of iron ore concentrate and increasing its recovery in flotation had been investigated compared to mechanical crushing. The aforementioned results of other researchers have been used in this study.

2. Experimental

2.1. Materials

The samples for this series of experiments were provided from the Golgohar iron mine (Kerman province, Iran), containing sulfide minerals. To prepare the samples, 250kg of samples were screened, and fine particles (<3.36 mm) were removed from the initial feed for the mechanical and electrical crushing investigations. In this case, d_{80} of the sample was changed from 11.245 mm to 15.341mm. Chemical analysis demonstrated that iron and sulfur grades were 48.9 and 1.9% in the initial sample. On the other hand, mineralogical studies proved that about 70% of the sample consisted of metallic minerals, and 30% were of gangue formation (quartz, chlorite, ...). The main minerals were magnetite, quartz, and chlorite; secondary minerals were hematite, pyrite, calcite, epidote, and biotite; and minor minerals were goethite and pyrrhotite. The major metal mineral (about 90%) was magnetite, and other metal minerals made up a small portion of the sample. Hematite was the second metallic mineral with an average abundance of 4-6%, where pyrite, pyrrhotite, and goethite were also represented by 2-4%.

2.2. Methods

For mechanical and electrical crushing, the main sample was divided into 1 kg subsamples. Experiments were performed on a lab-scale within the batch process. It is necessary to explain that the recent research applications of the electric crushing method were mainly done in three categories: process studies, energy consumption optimization, and device development, and by default, its energy consumption was higher than conventional crushing methods. In the present study, the issue had been studied from a process perspective, and the goal had not been to optimize or reduce energy consumption. However, for comparison and future studies, both methods' energy consumption (kwh/t) had been measured and compared in table 1. In the mechanical approach, laboratory jaw and cone crushers were selected, and in the electrical approach (HVEP), a high voltage electric pulse crusher (50Kv) was employed, and both samples were then crushed reach size lower than 3.36 mm. The crushed particles were then grinded, applying a rod mill to the size of finer than 150 microns. In order to ensure the uniformity of crushing and production of products with similar granulations, reproducibility was performed by performing several stages of sieve analysis of products resulting from mechanical, electrical, and rod grinding. Polished sections and polarized light microscope ZEISS model Axioplan 2 with reflective light were used in microscopic studies. To prepare/provide samples for further flotation tests, a magnetic separation step was accordingly used by a low-intensity roller magnet separator (1000 gauss), 45rpm, solid weight of 25%, and pulp inlet discharge of 4L/min.

2.3. HVEP pretreatment equipment

A schematic diagram of the high voltage electric pulse crusher (HVEP) is shown in Fig. 2, used to carry out electric crushing tests in the Iranian Mineral Processing Research Centre (IMPRC). This device has

two main parts: i) the electric pulse generation circuit and ii) the primary crushing compartment. The main compartment of crushing has a conductor of the copper electrode, which can transmit the generated shock waves from the electric circuit to the rock (Fig. 3).

Table 1. Comparison of mechanical and pulse electrical crushing energy consumptions

Initial crushing	Feed size (mm)	Product size (mm)	Total energy consumption (kWh/t)	Energy consumption for sample crushing (kwh/t)	Ratio of energy consumption for sample crushing to total energy consumption (%)
Mechanic	-20+3.36	-3.36	51.8	6.0	11.5
Pulse electric	-20+3.36	-3.36	81.0	14.4	18.0

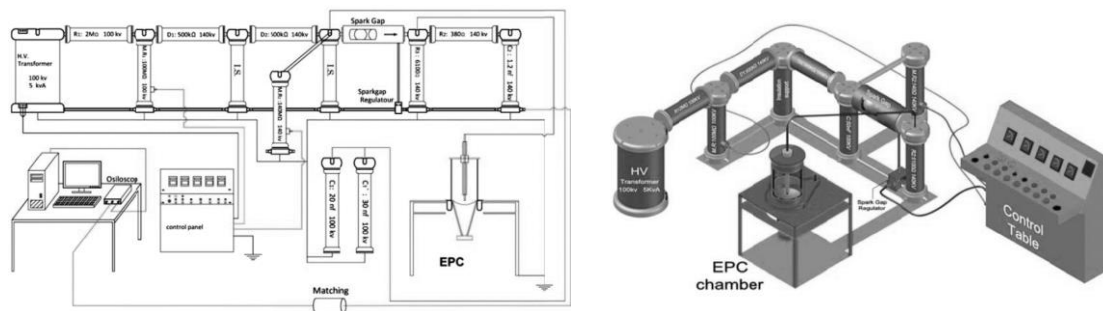


Fig. 2. Schematic diagram of the high voltage electric pulse crusher.

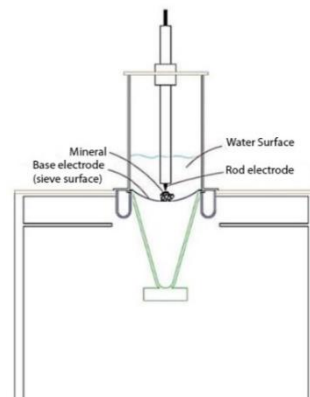


Fig. 3. Schematic diagram of the main compartment of the crushing unit.

2.4. Flotation experiments

This research performed the flotation tests using a mechanical 1 liter Denver laboratory flotation cell. As it is evident in Fig. 4, to decrease the sulfur amount in the iron ore concentrate and therefore achieve better flotation results, 150g/t Hydrogen Sodium Sulfide, 100g/t Potassium Amyl Xanthate and 100g/t Methyl Isobutyl Carbinol were used as activator, collector, and frother, respectively. The pulp density was adjusted to 25%, and the pH was about 8. Also, to investigate the kinetics of particles in the flotation of two samples of high sulfur concentrate with initial mechanical and electrical pulse crushing, flotation experiments with frothing times of 1, 2, and 3 minutes were performed on each sample, and sulfur content recovery of each stage of frothing was obtained.

3. Results and discussion

3.1. Effect of HVEP on comminution

According to the mechanical and electrical crushing tests (Fig. 5), the percentage of fine particles (-38

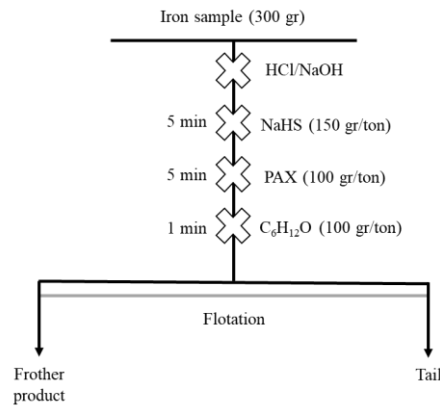


Fig. 4. Flotation flowsheet of the mineral

microns) in electrically crushed samples was lower than in mechanically crushed ones. It implied that, in general, crushed with electric pulses resulted in low slime production due to fracture with the aid of created tensile stresses and separation of particle borders. In contrast, according to the impact and abrasion, more slime production was inevitable in the mechanical approach. In addition, in the middle dimensions (-500+38 microns), there was no significant discrepancy between the two methods. However, in the coarser size range (-2360+500 microns), the percentage (abundance) of particles produced by the electrical approach was higher than the mechanical one because of the dielectric property variations of different minerals in which the electrical crushing in coarser size fractions presented a selective performance over mechanical approach. Based on the microscopic images of the crushed samples by both mechanical and electrical methods (Figures 6, 7 & 8), separation from boundaries, liberation degree, smoothness, cleanliness, and the preservation of crystal surfaces in the electrical method were more and better than the mechanically crushed samples.

Moreover, in Fig. 7, the separation of pyrite and magnetite from each other and the formation of microcracks employing electric pulses are shown in the -300+106 microns size fraction. According to the observations, in electrical pulse crushing, both pyrite and magnetite microparticles are well separated from each other's boundary, and microcracks have been created in pyrite and magnetite separately. Nevertheless, as shown in Fig. 8, in mechanical crushing, the boundaries of pyrite and magnetite existed, separation from the boundaries between pyrite and magnetite not occurred, pyrite and magnetite particles were involved, and no microcracks have been formed in the boundaries of these minerals.

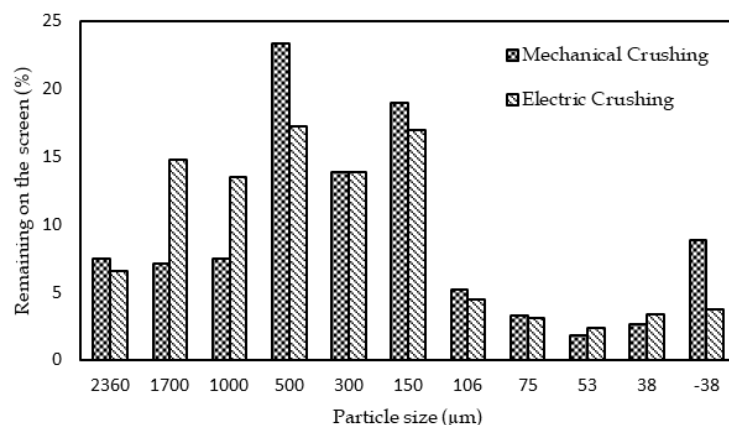


Fig. 5. Screening analysis of mechanically and electrically crushed samples

3.2. Effect of HVEP on grinding time

By noticing the grinding times with initial mechanical and electrical crushing (Fig. 9), the breakage of the samples in different periods proved that the initial electrical pulse crushing in comparison to initial

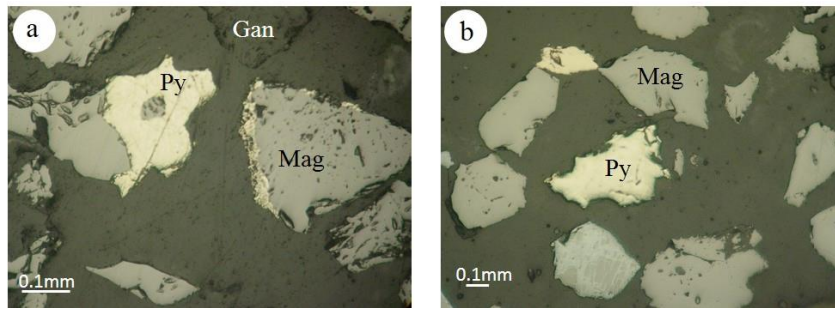


Fig. 6. Microscopic images of the crushed samples considering the crushing method: a) mechanical, b) electrical pulses

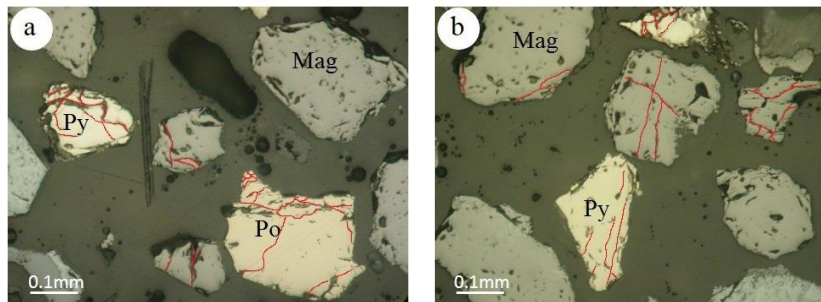


Fig. 7. Pyrite and Magnetite separation in size fraction -300+106 microns, and the creation of microcracks by electrical pulses crushing

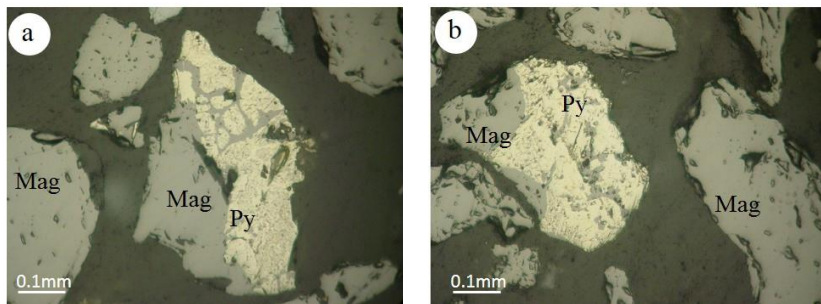


Fig. 8. Involvement of pyrite and magnetite in the size fraction -300+106 microns and the lack of microcrack creation in mechanical crushing

mechanical crushing made the breakage process to some extent, easier and faster to achieve a particular size. This was common in coarser size fractions, and in fine particles, it was not that effective, and the grinding times in both methods were nearly close and identical. The reason could be obtained from the microcracks created in coarser size fractions while initial electrical crushing was applied. So, it could be comprehended that grinding of such samples were easier and faster. In other words, when using initial electrical pulse crushing, a pre-weakening process causes the grinding operation to occur in a shorter time. The grinding time to reach $d_{80} = 150$ microns in the sample with initial mechanical crushing was 12 minutes and 30 seconds (12:30), and in the sample with initial electrical crushing was 11 minutes and 11 seconds. In this case, the difference in crushing time was 1 minute and 19 seconds, which was equivalent to about 12%.

3.3. Effect of HVEP on flotation recovery

The results in Table 2 explained that under similar conditions in feed size and grade, type and dosage of the reagents, conditioning and frothing times, sulfur grade and recovery of two samples were different due to initial crushing methods. The grade of sulfur in the iron ore concentrate sample employing initial high voltage electrical pulse crushing in the flotation residue was about 58% less than

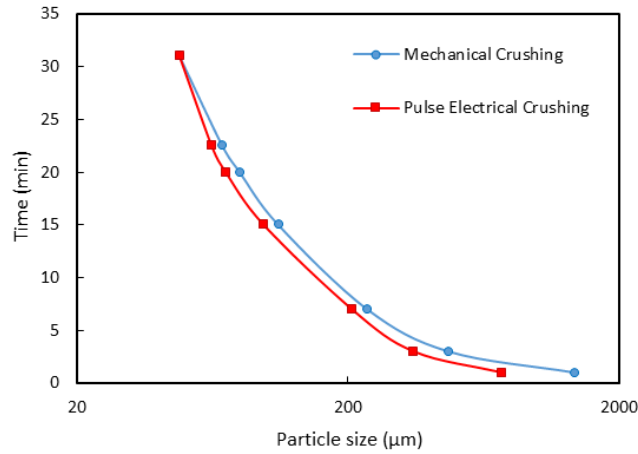


Fig. 9. Grinding time with applying initial electrical and mechanical crushing

the sample initially crushed mechanically, which was noticeable. Also, with attention to Fig. 10, the amount of recovery or removal of sulfur in the sample with electrical pulse crushing was more than in the sample with mechanical crushing. Thus, sulfur in the electrically crushed sample was floated at about 83.7%, while 73.1% of the sulfur was floated in the mechanically crushed sample. The results indicated that in the case of employing electrical crushing, the content of sulfur in the flotation froth was 10.6% more than mechanical crushing state. Also, table 3 showed the grade and recovery of iron in the froth zone. As could be seen, the grade of iron concentrate was to some extent equal in both crushing methods. Still, the grade and recovery of iron in the froth zone with initial electrical crushing were more than the mechanical initial crushing state. Due to the low recovery of iron in the froth, the slight difference between the two methods, and the fact that most of the iron measured in the froth was related to floating pyrite, it could be concluded that the amount of magnetite loss in the flotation froth had been somewhat negligible.

Table 2. Results of Sulfur grade and recovery based on the crushing method

The initial crushing	Size (microns)	Sulfur grade (%)			Sulfur recovery of the floated section (%)	
		feed	froth	residue	weight	content
Mechanical	150	1.18	19.18	0.33	4.5	73.1
Electrical	150	1.14	16.74	0.19	5.7	83.7

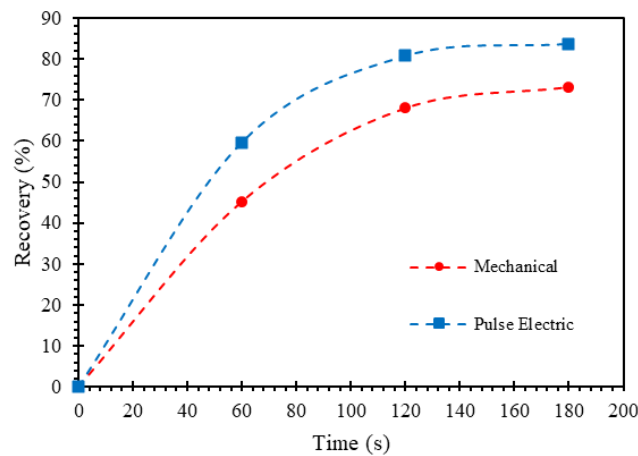


Fig. 10. Recovery of sulfur in the flotation of the initially crushed (mechanically and electrically) samples in different periods of frothing

Table 3. Results of Iron grade and recovery based on the crushing method.

The initial crushing	Size (microns)	Iron grade (%)			Iron recovery of the floated section (%)	
		feed	froth	residue	weight	content
Mechanical	150	66.4	26.1	68.3	4.5	1.8
Electrical	150	66.5	31.7	68.6	5.7	2.7

3.4. Effect of HVEP on flotation kinetics

As shown in Fig. 11, the constant of the flotation kinetics was reported to be 0.011 s^{-1} for the sample with the initial electrical pulse crushing and 0.008 s^{-1} for the sample with initial mechanical crushing. Obtained results indicate a 37.5% increase in the flotation constant when the electrical pulse crusher was applied, leading to a faster flotation process of the sample. The difference in the crushing method of samples could yield this issue of increasing flotation kinetics since all the effective parameters were kept fixed and did not change through the operation. As shown in Figures 6, 7 & 8, mineral separation from the connection boundary in the case of applying electrical pulse compared to mechanical crushing, presented an acceptable liberation degree and selective crushing since the produced particles were in good shape, and the flotation process was accomplished faster and much more accessible and efficient. The size analysis results of the froth (Fig. 12) also illustrated that the amounts of fine particles entering the froth zone were higher in the electric pulse crushing method than the mechanical one. Since the floating particles mainly consisted of sulfide minerals (pyrite), it would be inferred that in the sample with initial electrical pulse crushing, pyrite particles were finer than the mechanical one, which caused better floatability results and also accelerated the process kinetics as well.

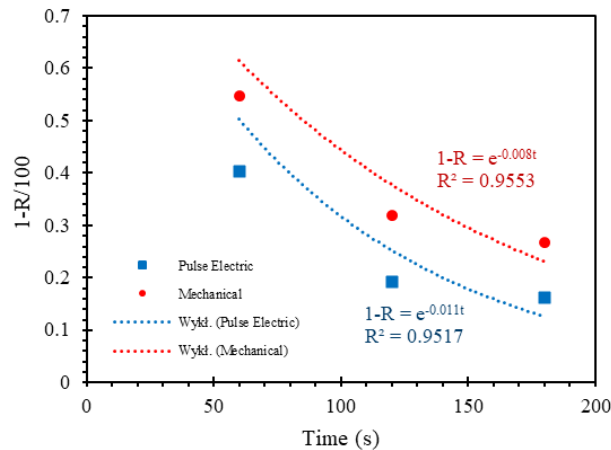


Fig. 11. The effect of initial crushing method on flotation kinetic constant

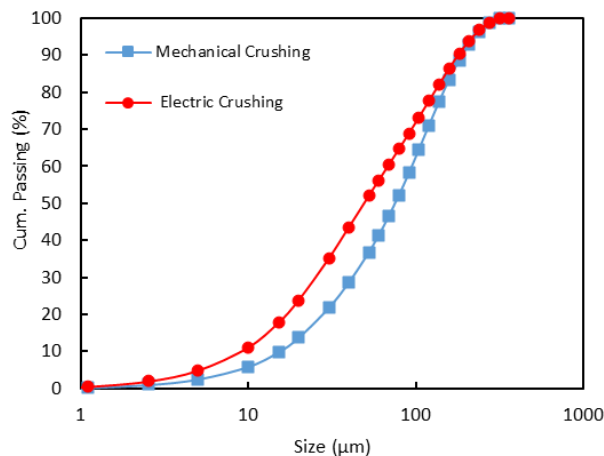


Fig. 12. The size analysis of the particles entering the froth zone related to two crushing methods

Also, microscopic studies of the -38 microns fraction of both samples (Fig. 13) indicated that the finer particles were dispersed in the sample, which was initially crushed by the electrical method, and there was space between them. In the mechanically crushed sample, finer particles formed an agglomerated shape due to the different comminution mechanisms. Thus, the metallic particles with identical charges were dispersed in the pulp because of higher zeta potential charge and impulsive forces, resulting in distancing the particles from each other and better preparation of the pyrite surface for reacting with chemicals and increasing the possibility of an air bubble collision. Therefore, the size and lightness of the pyrite particles in this range became an assistant factor, which led to a better and faster way of pyrite flotation and accelerated the flotation kinetics. While in the case of initial mechanical crushing, the process was not selective and due to impact and abrasion mechanisms, fine particles were produced with accumulation properties covering pyrite and preventing its flotation. This factor was recognized as an obstacle to flotation processing.

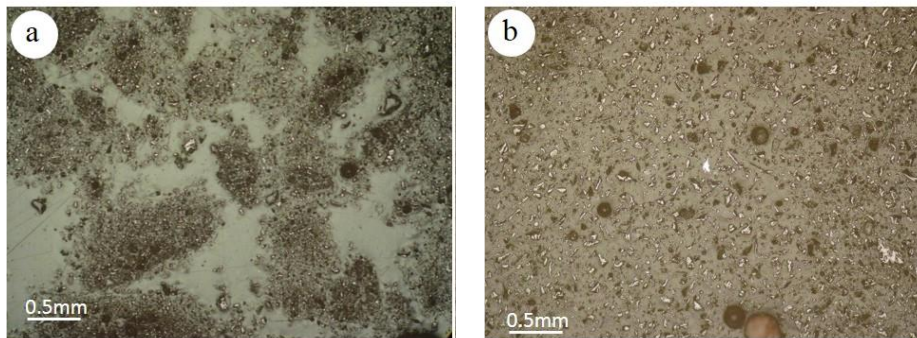


Fig. 13. Formation of the flotation residue particles in -38 microns fraction based on the crushing method:
a) mechanical method, b) electrical method

4. Conclusions

In the present study, the effect of initial crushing (mechanical and electrical pulse) on the flotation of iron ore with high sulfur content samples was investigated. The experimental observations demonstrated that in the initial crushing step employing electric pulses, to obtain a -3.36mm fraction, coarser particles were produced with fewer slimes (-38 microns). The reason for this issue comes from the difference in mineral dielectric constants. Mineralogical studies represented that separation from boundaries, liberation degree, smoothness, cleanliness, and the preservation of crystal surfaces in the electrical method were more and better than the mechanically crushed samples. Also, the high voltage electric pulse caused micro-cracks in minerals which led to pre-weakening and made the grinding somewhat easier and faster in the incoming stages besides the separation in the mineral boundaries.

Flotation remarks evidenced that in the electrically crushed sample, the sulfur grade of the iron ore reached from 1.14 to 0.19%, while in the mechanically crushed sample, this amount decreased from 1.18 to 0.33%. It means that the electrical pulse crushing reduces the sulfur grade of the iron ore concentrate up to approximately 58%. Also, the recovery of sulfur in the electrically crushed sample in the froth zone was 83.7%, and the mechanically crushed sample was reported to be 73.1%. Thus, the electrical crushing method showed better performance (10.6% higher) in sulfur recovery.

In addition, the results of flotation kinetics revealed that the flotation rates of these two types of crushing approaches were different. The kinetic constant in the electrical pulse approach increased by 37.5% compared to the mechanical method due to the variation in the amount and types of fine particles produced in the crushing process. The analysis of particle sizes in the froth zone presented that the fine particles in the froth zone in electrical crushing were more than the mechanical crushing method under the same conditions. Since most of the floated particles contained pyrite, it could be concluded that in the electric pulse crushing in comparison to the mechanical crushing, pyrite was liberated faster and reached to the finer fractions. Additionally, mineralogical studies proved that the finer particles (-38 microns) in the flotation pulp phase of the electrically crushed sample were dispersed, while they formed an agglomerated shape in the mechanical method. In this case, the dispersion of the particles in the electrically crushed samples resulted in better preparation of pyrite ore for reacting with chemicals

and increased the possibility of more collision to the air bubbles, which increased the floatability and flotation kinetics.

References

- ANDRES, U., JIRESTIG, J., TIMOSHKIN, I., 1999. *Liberation of minerals by high-voltage electrical pulses*. Powder Technology, 104(1), 37-49.
- ANDRES, U., TIMOSHKIN, I., JIRESTIG, J., STALLKNECHT, H., 2001. *Liberation of valuable inclusions in ores and slags by electrical pulses*. Powder Technology, 114(1-3), 40-50.
- ANDRES, U., 2010. *Development and prospects of mineral liberation by electrical pulses*. International Journal of Mineral Processing, 97(1-4), 31-38.
- CABRI, L. J., 2004. *New developments in process mineralogy of platinum-bearing ores*. Proceedings of Canadian Mineral Processors, 189-198.
- CABRI, L. J., BEATTIE, M., RUDASHEVSKY, N., RUDASHEVSKY, V., 2005. *Process mineralogy of Au, Pd and Pt ores from the Skaergaard intrusion, Greenland, using new technology*. Minerals Engineering, 18(8), 887-897.
- CABRI, L. J., CHOI, Y., HAMILTON, C., KONDOS, P., LASTRA, R., 2008. *Hydroseparation concentrates and automated precious metal searches used to characterise process products from selected mines*. 9th International Congress for Applied Mineralogy, ICAM.
- CABRI, L. J., RUDASHEVSKY, N. S., RUDASHEVSKY, V. N., GORKOVETZ, V. Y., 2008. *Study of native gold from the Luopengsulo deposit (Kostomuksha area, Karelia, Russia) using a combination of electric pulse disaggregation (EPD) and hydroseparation (HS)*. Minerals Engineering, 21(6), 463-470.
- HUANG, W., SHI, F., 2018. *Improving high voltage pulse selective breakage for ore pre-concentration using a multiple-particle treatment method*. Minerals Engineering, 128, 195-201.
- MERMILLOD-BLONDIN, R., KONGOLO, M., DE DONATO, P., BENZAAZOUA, M., BARRES, O., BUSSIÈRE, B., & AUBERTIN, M., 2005. *Pyrite flotation with xanthate under alkaline conditions-application to environmental desulfurization*. Centenary of flotation symposium.
- SARAVARI, A., SHAYANFAR, S., 2021. *Desulfurization of iron ore concentrate using a combination of magnetic separation and reverse flotation*. Journal of Chemical Technology and Metallurgy, 56(5), 1002-1110.
- SHI, F., ZUO, W., MANLAPIG, E., 2013. *Characterisation of pre-weakening effect on ores by high voltage electrical pulses based on single-particle tests*. Minerals Engineering, 50, 69-76.
- SHI, F., MANLAPIG, E., ZUO, W., 2014. *Progress and challenges in electrical comminution by high-voltage pulses*. Chemical Engineering & Technology, 37(5), 765-769.
- SHI, F., ZUO, W., MANLAPIG, E., 2015. *Pre-concentration of copper ores by high voltage pulses. Part 2: Opportunities and challenges*. Minerals Engineering, 79, 315-323.
- WANG, E., SHI, F., MANLAPIG, E., 2011. *Pre-weakening of mineral ores by high voltage pulses*. Minerals Engineering, 24(5), 455-462.
- YAN, G., ZHANG, B., DUAN, C., ZHAO, Y., ZHANG, Z., ZHU, G., ZHU, X., 2019. *Beneficiation of copper ores based on high-density separation fluidized bed*. Powder Technology, 355, 535-541.
- YAN, G., ZHANG, B., ZHAO, P., ZHUANG, S., ZHOU, E., ZHAO, Y., 2020. *Investigating the influence of mineral characteristics on induced effect of high-voltage pulse discharge by synthetic minerals*. Minerals Engineering, 153, 106380.
- YU, K.-p., YU, Y.-f., XU, X.-y., 2013. *Separation behavior and mechanism of hematite and colophane in the presence of collector RFP-138*. Transactions of Nonferrous Metals Society of China, 23(2), 501-507.
- YU, J., GE, Y., CAI, X., 2016. *The desulfurization of magnetite ore by flotation with a mixture of xanthate and dixanthogen*. Minerals, 6(3), 70.
- ZHANG, X., GU, X., HAN, Y., PARRA-ÁLVAREZ, N., CLAREMBOUX, V., KAWATRA, S., 2021. *Flotation of iron ores: A review*. Mineral processing and extractive metallurgy review, 42(3), 184-212.
- ZUO, W., SHI, F., MANLAPIG, E., 2015. *Pre-concentration of copper ores by high voltage pulses. Part 1: Principle and major findings*. Minerals Engineering, 79, 306-314.
- ZUO, W., SHI, F., VAN DER WIELEN, K. P., WEH, A., 2015. *Ore particle breakage behaviour in a pilot scale high voltage pulse machine*. Minerals Engineering, 84, 64-73.
- ZUO, W., LI, X., SHI, F., DENG, R., YIN, W., GUO, B., KU, J., 2020. *Effect of high voltage pulse treatment on the surface chemistry and floatability of chalcopyrite and pyrite*. Minerals Engineering, 147, 106170.