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Strengthen Leaching Effect of Carlin-type Gold via High-voltage Pulsed Discharge Pretreatment

Peng Gao[1,2], *Yong-hong Qin*[1,2], *Yue-xin Han*[1,2], *Yan-jun Li*[1,2], *and Si-ying Liu*[1,2]

1) College of Resources and Civil Engineering, Northeastern University, Shenyang 110819, China.

2) National-local Joint Engineering Research Center of High-efficient exploitation technology for Refractory Iron Ore Resources, Shenyang 110819, China

Corresponding author: Yong-hong Qin

E-mail addresses: qyh_neu@163.com;

Abstract

High-voltage pulsed discharge (HVPD) pretreatment was applied to strengthen the leaching effect of Carlin-type gold ore containing arsenic in this work. The optimal results of pretreatment experiments was obtained at the operating conditions of spherical gap spacing 20 mm, pulse numbers 100, and input voltage 90 V. The leaching rate of gold were increased by 15.6% via HVPD pretreatment. The mass fraction of -0.5+0.35 mm and -0.35+0.1 mm were increased by 11.0% and 6.8% compared with untreated samples, respectively, and the Au grade of -0.1 mm was increased by 22.8%. However, the superiority of HVPD pretreatment would be weakened by prolonging grinding time. Scanning electron microscope (SEM) results indicated that the pretreated products presented in the state of melting and then condensation, accompanying by some pore formation. More micro-cracks were generated in the interface of ore and the original crack were expended via pulsed discharge pretreatment, with the contact area between leaching reagent and ore were enlarged, and the leaching reaction rate were enhanced and the leaching effect was strengthened.

Keyword: High-voltage pulse discharge pretreatment; Carlin-type Gold; Leaching rate; Particle size distribution; Microcracks

1. Introduction

In recent decades, with the rapid development of the gold industry, the intractable gold mine has become an important resource, accounting for 30% to 40% of the total reserves [1]. Some gold ore are rich in arsenic, carbon and other impurities, resulting in a low leaching rate of gold via conventional leaching conditions, which are named as refractory gold ore [2]. The cyanide agitation leaching rate of the difficult gold ore is generally less than 80%, and the leaching rate of some gold mine as low as 10% [3-4]. Most of the refractory ore are wrapped by silica, carbonate, pyrite or arsenopyrite, and it is difficult to realize efficient contact of the gold and cyanide solution by grinding. Therefore, it is particularly important to pretreat refractory gold ore for increasing the leaching rate [5-7].

In the existing technical conditions, pretreatment of refractory gold ore is usually carried out by calcination, wet chemical, pressurized oxidation and biological oxidation, which have a number of defects [8]. For instance, the energy consumption of the roasting pretreatment are high, and the leaching rate is obviously effected by over-roasting and under-sintering. The wet chemical method is sensitive to the changes of minerals, process conditions and environment. The pressurized oxidation method requires high intensity equipment [9], meanwhile the investment cost and energy consumption are relatively high. The biological oxidation law has the disadvantages of long production cycle and low productivity [10-11]. Therefore, it is significant to adopt innovative pretreatment approach to improve the leaching rate of refractory gold ore.

High-voltage pulsed discharge breakage (HVPDB) is an innovative technology [12-13]. Based on the difference properties of interface mineral components, in virtue of pulse discharge, minerals are broken and dissociated along their grain boundaries preferentially, and the metallic minerals and gangue are liberated at the condition of coarse particle size [14-16], thereby the energy consumption of grinding is reduced and the separation indicators are improved [17-21]. HVPDB is the optimal method of breaking along the grain boundary, which produces extended cracks at the mineral interface inside the ore, thereby enhancing mineral liberation and separation characteristics [22-24].

The HVPDB was employed to pretreat quartz ores based on the characteristics of selective breakage [25]. The rock inclusions of quartz were broken to reduce the pollution of associated ores on quartz crystals, so as to meet the production of high purity silicon raw materials for solar cells. The area of cracks and microcracks in the

HVPDB samples was four times than mechanical breakage (MB) product, and the strength of HVPDB sample was lower than MB products. The grinding experiments showed that the energy economization of grinding process was 24% [26]. Complete liberation and a narrow-fraction of metal concentration were obtained by HVPDB, which indicated that 97.92% copper was accumulated in the 2 mm products [27]. The HVPDB samples presented higher liberation in each size fraction; the liberation of pretreated samples was 13.19% higher than MB products. [28]. The electric pulse wave contributed to redevelop and expand the microstructure existing in coal rock mass [29], which caused the coal rock fissure to sprout and expand until the destabilization disintegration was a fatigue fracture. A HVPD pretreatment of improving the permeability of coal seams was conducted by Zhu et al. (2018) [30]. The tensile stress generated by transient high temperature caused the external fracture of the coal. The porosity of coal with different particle sizes (micropore, mesopore and macropore) increased after HVPDB.

In the present work, an innovative technology of HVPD pretreatment was proposed for Carlin-type gold ore to strengthen the performance of leaching, the influence of spherical gap spacing, input voltage and pulse number on leaching of pretreated samples were researched. The liberation of breakage samples was observed under the optical microscope. The SEM were adopted to observe morphology and surface microcracks.

2. Materials and methods

2.1 Process mineralogical

The Carlin-type gold deposit containing arsenic and antimony was obtained from Zaozigou, Gansu province. The results of chemical multi-element analysis of ores (Table 1) indicated that the main elements were silicon, aluminum, calcium, and iron, followed by a small amount of copper, lead, zinc, and sulfur, accompanying with the grade of gold was 3.38 g/t. In addition, carbon, arsenic, and antimony in ores would reduce the leaching rate of low gold.

Table 1. The multi-element analysis of ore

Element	Au*	Ag*	Cu	Pb	Zn	Fe	C	S
Content (%)	3.38	1.0	0.006	0.005	0.012	3.27	2.06	0.84

Element	Sb	As	SiO_2	Al_2O_3	Ca	MgO	TiO_2
Content (%)	0.47	0.41	56.46	14.67	5.56	2.81	0.57

Note: *unit is g/t

Table 2. The statistical results of mineral composition and content

Mineral	Quartz	Carbonate	Mica	Feldspar	Pyrite	Dalarnite	Stibnite
Content (%)	32.67	29.24	27.45	4.57	0.94	0.86	0.63

The results of mineral composition and content analysis (Table 2) indicated that the content of non-metal was very high, among which the contents of quartz, carbonate, and mica were 32.76%, 29.24%, and 27.45%, respectively. On the contrary, the contents of pyrite, dalarnite, and stibnite were 0.94%, 0.86% and 0.63%, respectively. Gold minerals mainly existed in the form of natural gold, which was 99.07%, and the relative content of electrum was only 0.93% (Fig. 1).

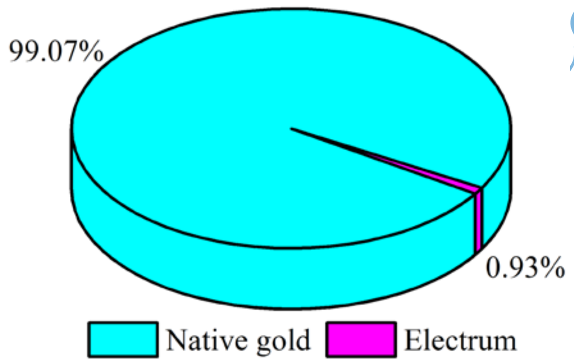

Fig. 1. The statistics of relative content in gold mineral

The occurrence of gold minerals had great influence on grinding and leaching. Therefore, it was particularly important to ascertain the occurrence of gold minerals. Most of the gold minerals were distributed in gangue, a few were enclosed in stibnite or embedded in the margin of stibnite, and a few were associated with sphalerite (Fig. 2).

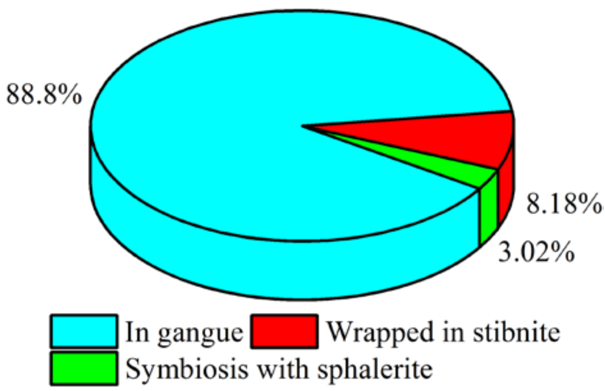

Fig. 2. The statistics of gold mineral particle morphology

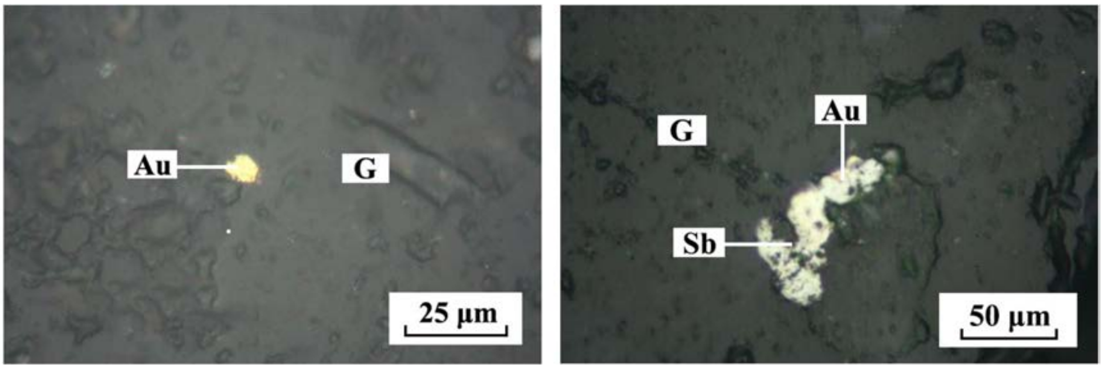

Fig. 3. Optical microscope photograph of gold

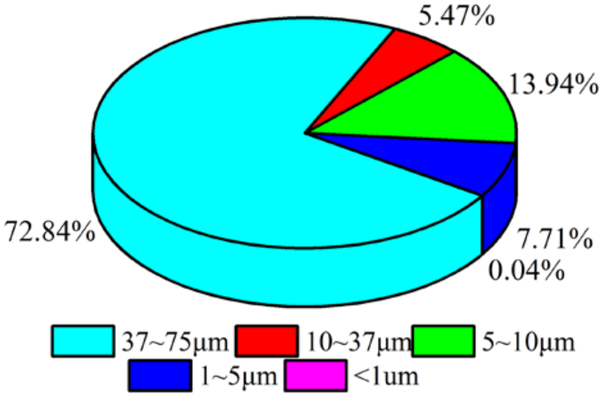

Fig. 4. The gold mineral embedded particle size statistical results

As shown in Fig. 4, the size of gold minerals was mainly in 37~75µm, with the content of 72.84%, followed by micro and fine-grained, with the content of 21.65% and 5.47% respectively, and the content of sub-micro-grains was very low, accounting for only 0.04%.

2.2 Experimental flow

The optimum conditions of leaching experiment were confirmed: grinding quality 60 g, grinding concentration 70%, grinding fineness of -74µm accounted for 90%, the dosage 10 kg/t, the ratio of liquid-solid 4:1, the leaching pH 11, the leaching temperature 30℃, the leaching time 6 h.

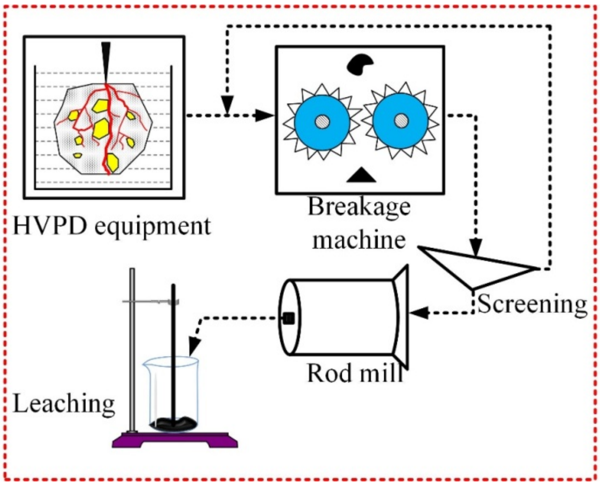

Fig. 5. Schematic diagram of experiment flow

10.0 g leaching residue of gold ore was placed in beaker, and 100 mL aqua regia were added and boiled 1 hour, then cooling to 25℃. The liquid in the beaker was filtered in the activated carbon adsorption column. The beaker and adsorption column were cleaned with dilute hydrochloric acid and deionized water, so that all dissolved gold in the ore sample was adsorbed by activated carbon. Activated carbon was burned in a high temperature furnace. The ashes were dissolved in aqua regia. The content was determined by flame atomic absorption spectrophotometer. The leaching rate was calculated according to the following Equation 1.

$$L = \left(1 - \frac{w_1}{w_0} \times \beta\right) \times 100\% \tag{1}$$

Where: L: Leaching rate

w_1: The gold grade of leaching residue

w_0: The gold grade of raw ore

β: Leaching residue productivity

2.3 Analytical and Equipment

The microscopic morphology obtained by the backscattered imaging method, which could distinguish elements according to the imaging color directly, and the color manifested a trend from dark to light according to the atomic number from small to large. In virtue of different elements possessed diverse X-ray characteristic wavelength, each atoms held dissimilar X-ray energy. Energy spectrometer was used for component analysis according to the characteristics of different X-ray energy.

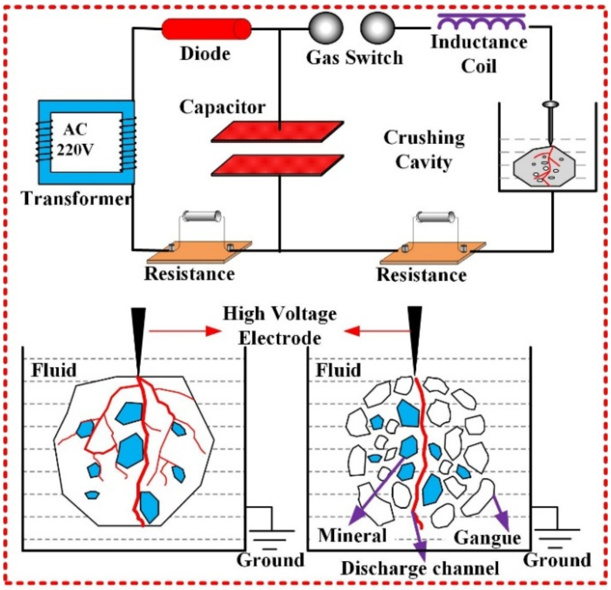

Fig. 6. Schematic Chart of Ore Fragmentation under HVPD

The liberation of mineral was defined as the percentage of monomer dissociated particles in the same particle size, which was the percentage of the total number of particles containing the mineral in the group (Equation 1).

$$F = \frac{f}{f + \sum f_i} \times 100\% \qquad (2)$$

Formula: F : the liberation of the mineral;

f : Number of individual dissociated particles of the mineral;

$\sum f_i$:Number of connate particles containing the mineral.

A representative sample of the grinding product were screening and classified (screen size: 0.074 mm, 0.045 mm, 0.037 mm) to obtain four different size products. A certain amount of samples were separated from each grain grade by mixing well, and the samples were placed on glass slides to make light sheets. The particles of each mineral monomer and the number of connectives with different ratios (0, 1/8, 1/4, 3/8, 1/2, 5/8, 3/4, 7/8, 1, etc.) were determined under polarized light microscope.

3. Results and discussion

3.1 Pretreatment experiment

3.1.1 Spherical gap spacing

Spherical gap spacing is the important section of gas switch in pulse discharge equipment. The size of spacing determines the frequency of loading voltage. The pulse number 100, the input voltage 90 V were confirmed, with the spherical gap spacing 15 mm, 20 mm, 25 mm, and 30 mm, respectively. The relationship between -74μm content, leaching rate and spherical gap spacing were indicated in Fig. 7.

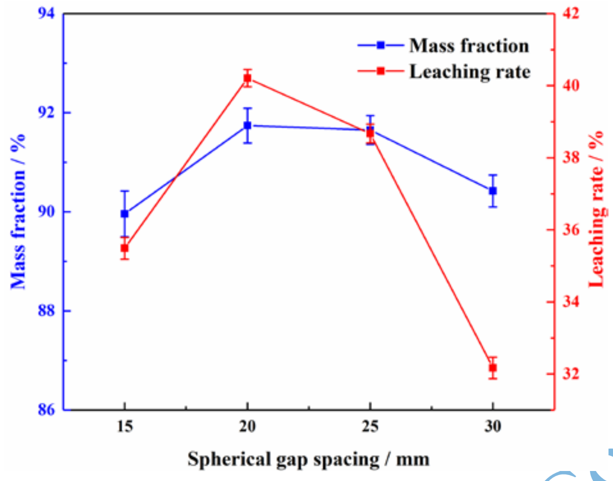

Fig. 7. Effect of spherical gap spacing on mass fraction and leaching rate

As shown in Fig. 7, the content of -74 μm and the leaching rate peaked at spherical gap spacing of 20mm. When the spherical gap spacing was 20 mm and 25 mm, the fraction of -74 μm in grinding products were 91.74% and 91.65% respectively, and the corresponding leaching rates were 35.49% and 40.21% respectively. The increasing in the spherical gap spacing resulted the breakdown voltage increased, which resulted in the enlargement of voltage loaded on the ore surface. However, when the gap spacing was enough large, the discharge volume between gas switches and the interval time increased, resulting that most of the electricity was released into the air and the electricity loaded on the surface of ore decreased relatively, which resulted in a weakening of the crushing effect. Therefore, the content of -74 μm particle size in grinding products decreased relatively. Excellent experimental results could be obtained at the suitable spherical gap spacing of 20 mm.

3.1.2 Pulse number

The pulse number determines the energy applied to the ore, setting the input voltage 90 V, the ball gap spacing 20 mm, and the pulse number 40, 60, 80, 100, and 120, respectively. The effect of pulse number on -74 μm content and leaching rate were illustrated in Fig. 8. As shown in Fig. 8, the content of -74μm in grinding products increased gradually with pulse number. While the pulse number exceeded 100, the content of -74μm in grinding products tends to be stable.

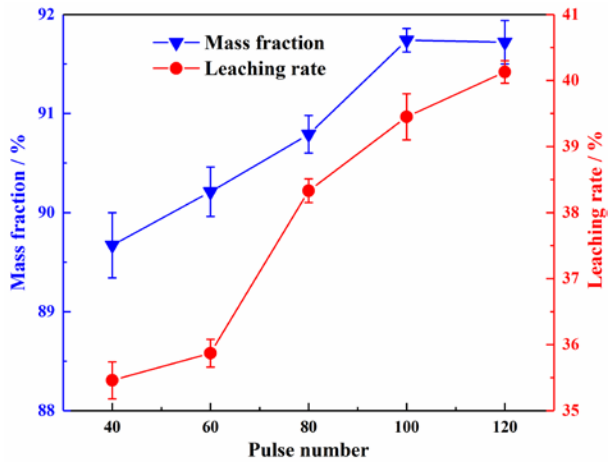

Fig. 8. Effect of pulse number on mass fraction and leaching rate

The time of HVPD was prolonged with the pulse number, and the effect of HVPD was strengthened to aggravate the breakage of ore. The pretreated ore was easily to grind in the subsequent operation, thus the fineness of the grinding product were improved. The enlargement of pulse number led to the higher liberation, promoting the contacting surface between leaching agent and gold mineral, accelerating the leaching reaction rate and improving the leaching effect.

3.1.3 Input voltage

The primate input voltage determines energy loaded in the ore, which had an effect on breakage and leaching of ore minerals. Setting the ball gap spacing 20 mm, the pulse number 100, the input voltage 70 V, 80 V, 90 V, 100 V, and 110 V, respectively, the effect of input voltage on -74 μm content and leaching rate in grinding products were exhibited in Fig. 9. During the appropriate range of voltage, the rising voltage resulted in more energy, which was contribute to promoting the -74μm content and leaching rate. However, with the further enlargement of voltage, the air switch was easy to breakage and the pulse frequency expedited, resulting the energy applied to the ore reduce, which was unfavorable to promote the ore breakage. In addition to, the long-time of high-voltage shortened the service life of equipment. Therefore, the appropriate voltage was 90 V.

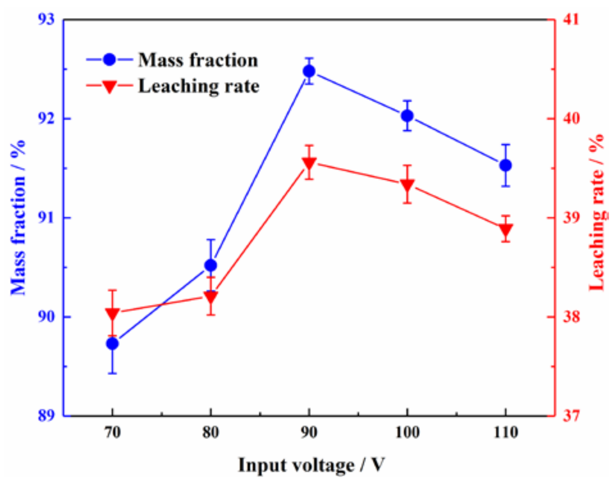

Fig. 9. Effect of input voltage on mass fraction and leaching rate

3.2 Comparison of grindability and leaching indexes

Based on the pretreatment experiment, setting the ball gap spacing 20 mm, the pulse number 100, the input voltage 90 V respectively, the grinding curve was indicated in Fig. 10 (a). What derives from Fig. 10 (a) was that grinding efficiency was improved via HVPD pretreatment. The relative grindability was defined as Equation 3, which was displayed in Fig. 10 (b).

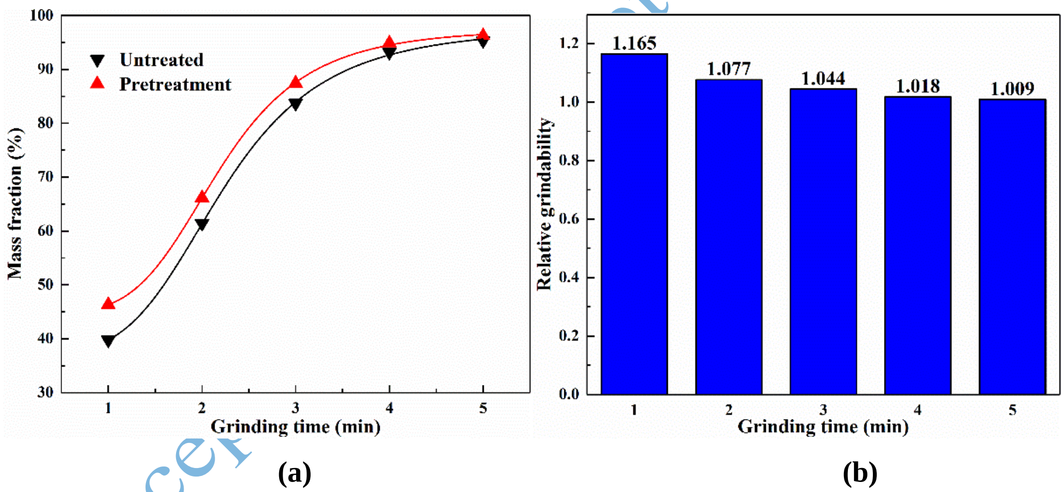

Fig. 10. Grinding curve (a) and relative grindability (b) of HVPDB products

The computational formula of relative grindability (k) is shown as follow.

$$k = \frac{m_p}{m} \tag{3}$$

Where M_p represents the −74 μm mass fraction of HVPD pretreatment; M is the -74 μm mass fraction broken by mechanical crushing at the same grinding time.

With the extension of grinding time, the mass fraction of -74 μm appeared an increasing trend, and the mass fraction of HVPDB was higher than MB. It was concluded that HVPD had an effect on promoting grinding efficiency and the relative grindability decreased with the grinding time, while the advantage of HVPD pretreatment were weakened by extending the time.

The leaching experiment were carried out at spherical gap spacing 20 mm, pulse number 100, input voltage 90 V, grinding fineness -74 μm accounts for 90%, dosage of reagent 10 kg/t, liquid-solid ratio 4:1, leaching pH 11, leaching time 6 h, leaching temperature 30℃.

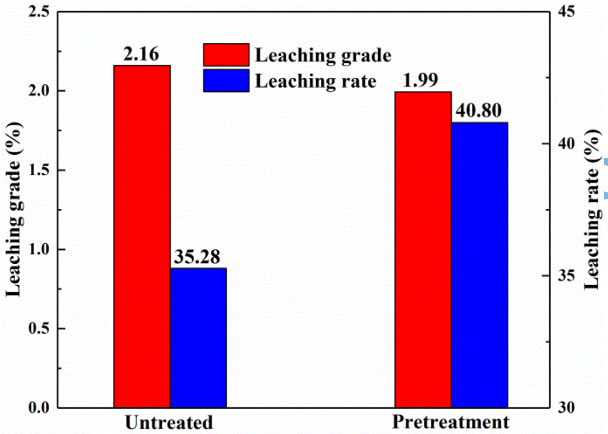

Fig. 11. Comparison of leaching indexes between pretreatment and untreated samples

According to Fig. 11, the leaching residue gold grade of MB was 2.16 g/t, and the leaching rate was 35.28%. The leaching residue gold grade of HVPDB was 1.99 g/t, and the leaching rate was 40.80%. It was concluded that the leaching rate of gold ore had been obviously increased by 15.65% via HVPDB. Due to the action of high voltage, the liberation of ore increased. More gold was exposed with grinding, the contact surface between leaching agent and gold were enlarged effectively. More micro-cracks and cracks were generated in the ore by HVPD pretreatment, resulting in that the leaching agent entered into the ore along the cracks, enlarging the contact area between the leaching solution and the gold mineral, increasing the leaching reaction rate, and thus improving the leaching effect significantly.

3.3 Particle size distribution and liberation

What concluded from Fig. 12 was that the fine particle content of HVPDB products was higher than MB products. The +1 mm, -1+0.5 mm content of HVPDB products were 1.19 and 1.53 percentage points less than MB products. The -0.5+0.35 mm, -0.35+0.1 mm content of HVPDB products with were 1.51, 1.20 percentage points higher than MB products respectively.

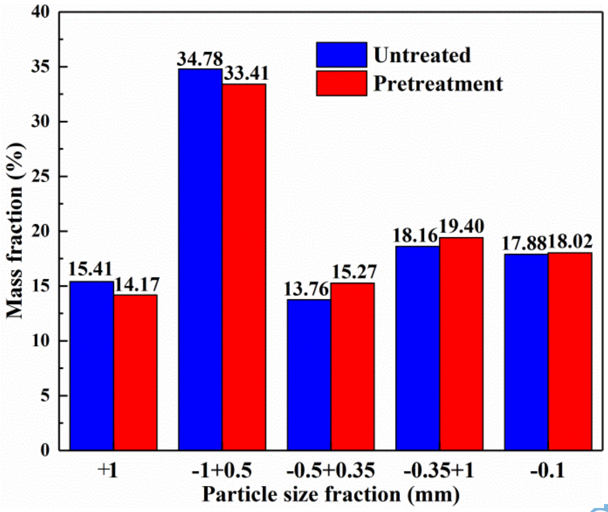

Fig. 12. Particle size distribution of comminution products

The Au grade of HVPDB products was obviously higher than MB products. The Au grade of HVPDB products in -1+0.5 mm, -0.25+0.1 mm, -0.1 mm particle size were 0.14, 0.11, and 1.11 percentage points higher than MB products, respectively.

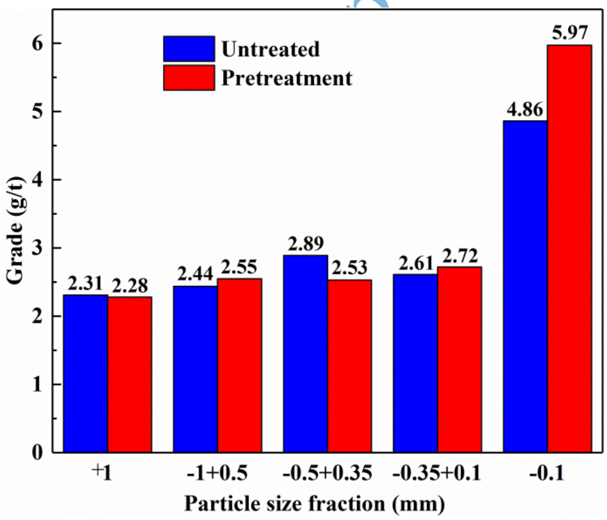

Fig.13. The Au grade of different particle size in comminution products

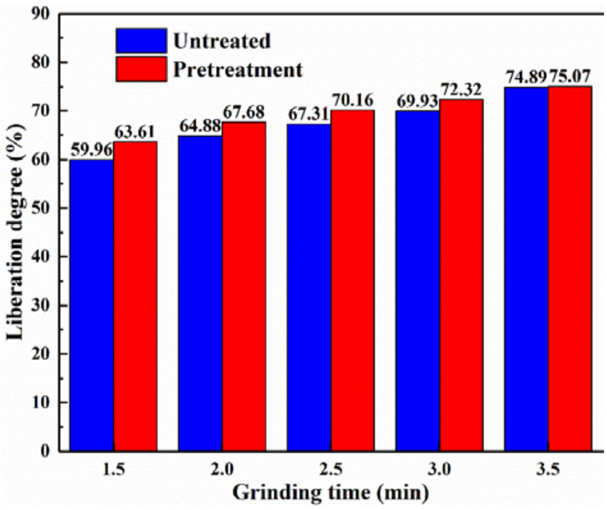

Fig. 14. Effect of grinding time on comminution products liberation degree

Polarization microscopy was adopted to determine the liberation of comminution products obtained from HVPDB and MB at different grinding time. The leaching rate were effected by liberation, which increased with grinding time, indicating that extending the grinding time would be conducive to achieve the high liberation. Besides, the contacting area between leaching agent and gold mineral were enhanced by HVPDB, resulting in that leaching rate was strengthened. In addition to, with the prolongation of grinding time, the differential value between HVPDB and MB experiment decreased gradually, indicating that the advantage of HVPDB would be weakened via prolonging grinding time.

3.4 Microstructure

What displayed in Fig. 15 were surface crack diagrams of MB and HVPDB products, respectively. It was concluded that the fracture surface methods were rough. Crushing and impact were the main methods of mechanical crushing, which determined the force between different particles was mainly produced by surface contact and point contact, resulting the distinct fracture surface. The MB products presented the characteristic that various forms and wide distribution (Fig. 15).

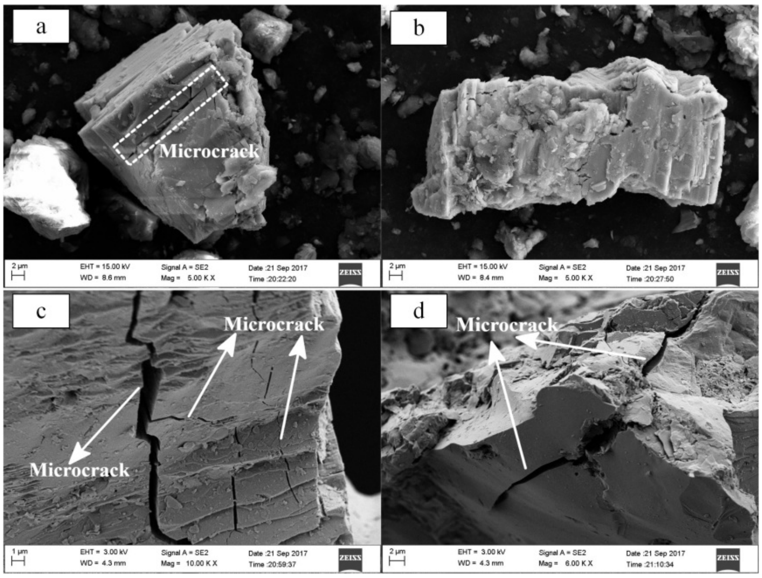

Fig. 15 SEM images of untreated sample (a) and pretreated products (b, c, and d)

The content of gangue was 96.96% in this experiment, while the permittivity and conductivity of quartz, carbonate minerals and sericite were similar, thus most microcracks generated in intragranular. After HVPD pretreatment, the number of microcracks was increased. Due to the action of HVPDB, the original micro-cracks developed and extended, thus the grindability of the ore were increased. It showed that the liberation characteristics and leaching index were enhanced by HVPD pretreatment.

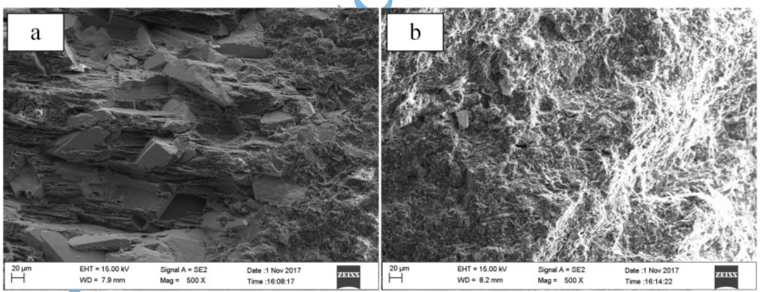

Fig. 16 SEM images of untreated sample (a) and pretreated products (b)

There were a lot of stoma marks on the fracture surface of the crushed product after HVPD pretreatment (Fig. 15), which indicated that the state of being melted, then cooled and solidified. When the gold ore was broken by HVPD, the discharge channel would be generated rapidly [14-18], and the temperature of discharge channel would rise sharply, resulting in the expansion of discharge channel and the generation of shock wave, which promoted the interfacial dissociation between metal and non-metallic minerals [19-21].

In addition, the high-temperature environment caused the melting of minerals near the discharge channel, and produced a large number of volatile gases [28] such as SO_2, H_2O, CO_2, etc. During the gas diffusion process, a large number of pores generated on the mineral surface.

When the HVPD was over, the high-temperature molten mineral re-solidify at low temperature. Therefore, a clear solidification morphology after melting appeared on the surface of HVPD samples. Meanwhile, there were many micro-cracks on the surface of gold ore, and SO_2, H_2O, CO_2 and other gases might enter the cracks quickly and exerted pressure on their inner walls, resulting in the original cracks extending along the direction perpendicular to the pressure, and then growing into a cross-section and realizing gold ore fracture.

4. Conclusions

1. The experiments of HVPD pretreatment are performed for Carlin-type gold ore containing arsenic, which indicates that the optimum operating parameters are gap spacing 20 mm, pulses number 100 and input voltage 90 V. With the aid of HVPD pretreatment, the leaching rate of gold ore increases by 15.6%. More micro-cracks and cracks are generated in the ore via pretreatment. The leaching agent enters into the ore along the cracks, enlarging the contact area between leaching solution and gold minerals, and the leaching reaction rate is improved obviously.

2. The fines content of HVPDB products is higher than MB products. Among them, the contents of -0.5+0.35 mm and -0.35+0.1 mm are 11.0% and 6.8% higher than MB samples, respectively, and the Au grade of -0.1 mm with pretreatment is 22.84% higher than MB samples. The liberation of HVPDB samples is higher than MB sample. The liberation increases with the prolongation of grinding time, but the performance of HVPD pretreatment will be weakened by prolonging grinding time.

3. After HVPD pretreatment, a lot of pore marks appear on the fracture surface of product, indicating a state of melting, then cooling and solidification. The high temperature environment causes the mineral melting near the discharge channel. A large number of volatile gases such as SO_2, H_2O and CO_2 will be produced, and many pores will be generated on the mineral surface during the gas diffusion process.

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