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Experimental Study on the Effect of Pretreatment with High-Voltage Electrical Pulses on Mineral Liberation and Separation of Magnetite Ore

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Abstract: High-voltage electrical pulses (HVEP) technology was applied in grinding of a magnetite ore as a comminution pretreatment. The effect of HVEP pretreatment on grindability, liberation and separation performance of a magnetite ore was investigated by a systematic experimental study. The results showed that the pretreatment of high-voltage electrical pulses created some intergranular microcracks inside the ore, reduced the mechanical strength and improved liberation. This gave the additional advantage of further breakage, thereby reducing the energy consumption and grinding time. In addition, the HVEP pretreatment before grinding was potentially beneficial in the recovery of the liberated minerals in the subsequent magnetic separation.

Keywords: high voltage electrical pulses; intergranular microcracks; grindability; mineral liberation; magnetic separation

1. Introduction

Research into high-voltage electrical pulses (HVEP) technology began in the 1930s with using capacitors to discharge electricity for producing X-rays [1,2]. After decades of research, HVEP technology has been successfully used in areas such as food sterilization, food processing, wastewater treatment, mineral processing, solid waste recycling, and metal material processing [3–7]. The disintegration of solid materials immersed in dielectric liquid (usually water) (shown in Figure 1), is an environment-friendly and efficient mineral liberation technology, which involves electrical breakdown induced by high-voltage electrical pulses [8–11].

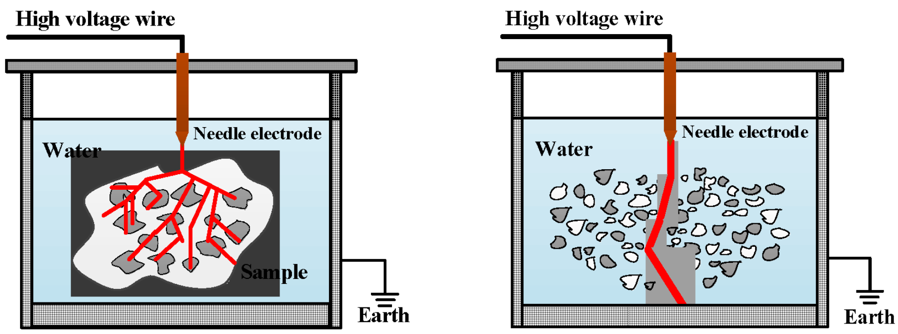

Figure 1. Schematic diagram of showing the disintegration of solid particles by high-voltage electrical pulses.

The effect of high-voltage electrical pulses on breaking rocks has attracted the interest of investigators with the recent development of HVEP technology [12–14]. There are a number of reports demonstrating the effectiveness of mineral liberation by high voltage electrical pulses [15–17]. Andres et al. [18] reported that the liberation properties of precious and base metal ores, such as emeralds, platinum group of metals (PGM), gold, and chalcopyrite, can be enhanced through the use of high-voltage pulse breakage. Yan et al. [19] confirmed that under the action of HVEP, the coal sample is broken down into multiple small pieces, and the degree of coal fragmentation increases with an increase in the breakdown voltage. Ito et al. [20] found that the electric disintegration resulted in preferential breakage of coal substances and mineral particles along their boundaries.

Magnetite ore is a composite substance which contains many types of minerals with a wide size and component distribution. Deposits of magnetite ores are widely distributed in the world. The main obstacle associated with exploiting these deposits is the poor liberation of iron minerals from gangue minerals, attributed to the complicated dissemination of valuable and gangue minerals. Meanwhile, the study of HVEP technology applied as a pretreatment in the grinding process of magnetite ore has been rarely reported. The purpose of this paper is to present the application of HVEP technology in reducing the mechanical strength and improving liberation. Magnetite ore treated with and without HVEP pretreatment before grinding, the influence of operation factors affecting the grinding efficiency, subsequent separation performance and morphology characteristics were investigated.

2. Materials and Methods

2.1. Magnetite Ore Sample

The magnetite ore sample used in the experiments was obtained from Dagushan Iron Mine in Liaoning, China. The sample was crushed and screened for a size of −2.0 mm. The chemical compositions of sample are shown in Table 1, which shows that the iron ore sample consist of TFe (total Fe) with a SiO_2 of 30.67% and 45.77%, respectively. The X-ray diffraction pattern of the sample is shown in Figure 2, which illustrates that magnetite is the main iron-bearing mineral, while quartz is the main gangue mineral.

The petrographic description highlighting the main minerals present within the iron ore sample can be seen in Table 2, which was determined by examining polished thin sections under an optical microscope. Two photomicrographs of the magnetite ore are shown in Figure 3, where some minerals are indicated. The petrographic results suggest that the iron ore sample is a fine-grained magnetite-quartzite with seriate poikilitic texture as well as mainly euhedral and subhedral grains.

Table 1. Chemical compositions of studied iron ore sample (mass fraction, %).

TFe	FeO	SiO_2	Al_2O_3	MgO	CaO	P	S
30.61	17.49	45.77	1.12	2.75	1.27	0.035	0.18

TFe: Total iron content.

Table 2. Mineral composition of studied iron ore sample (mass fraction, %).

Magnetite	Hematite	Pyrite	Quartz	Carbonate Minerals	Sericite	Chlorite	Others
35.51	1.44	0.54	49.98	9.37	1.87	1.26	0.03

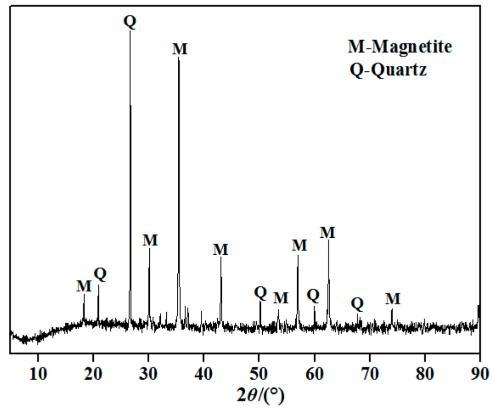

Figure 2. X-ray diffraction pattern for the studied magnetite iron ore.

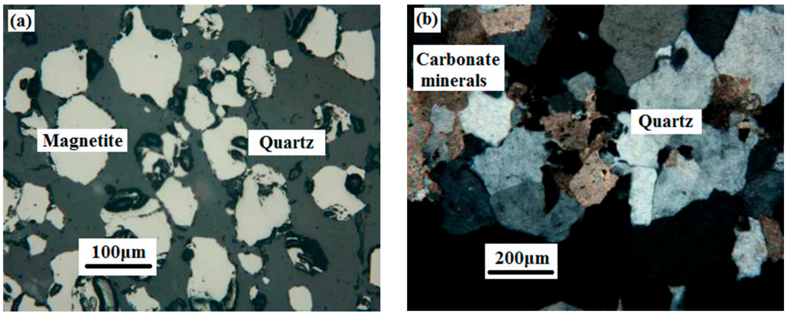

Figure 3. Photomicrographs of studied magnetite iron ore (**a**) taken under reflected light and (**b**) taken under polarized light.

2.2. HVEP Pretreatment Equipment

The high-voltage electrical pulses (HVEP) pretreatment equipment with high-voltage electrical power is developed, while the schematic diagram of this equipment is shown in Figure 4. The equipment contains a transformer, a capacitor, a ball gap switch, a needle electrode and a HVEP breakdown cavity. The needle electrode and plate electrode are installed in the HVEP breakdown cavity. The needle electrode, which acts as discharge electrode is connected to the high-voltage wire. Deionized water is used as the dielectric liquid to induce plasma channels into the samples. The high-voltage electrical power unit transforms 220 V/50 Hz power supply voltage alternating current into direct current, which charges the transformer and capacitor. The high-voltage electrical power can output a maximum voltage of 50 kV, while the capacitance of the capacitor is 5600 PF.

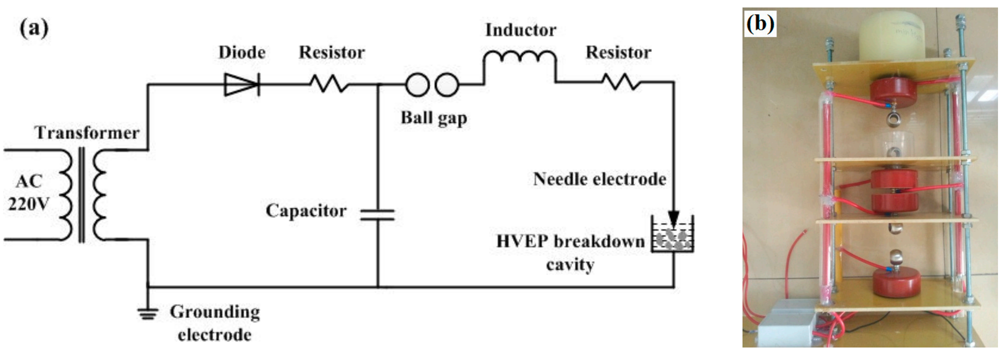

Figure 4. (**a**) Schematic diagram and (**b**) photo of HVEP pretreatment equipment.

2.3. Experimental Procedure

The experimental procedure includes the HVEP pretreatment of sample, grinding test, and magnetic separation. A total of 200 g magnetite ore samples was placed in the HVEP breakdown cavity with deionized water. Determination of the relative grindability of the untreated and treated samples was conducted by measuring the particle size distribution after the grinding process. The products treated with HVEP pretreatment and samples chosen as a reference without HVEP pretreatment were ground into powder form in a laboratory rod mill at a predetermined time [21]. After grinding, the particle size distribution was estimated by the particle-screening sieve screening while degree of mineral liberation was measured by light microscope [22–24]. In order to investigate the influence of HVEP pretreatment on the subsequent magnetic separation, the magnetic separation of samples with and without HVEP pretreatment was carried out, the magnetic separation time was 5 min and the magnetic field intensity was 110 KA/m.

The morphology and microstructure of products with and without HVEP pretreatment were observed by scanning electron microscopy (SEM; S-3400N; Hitachi, Ltd., Tokyo, Japan) and composition analysis was carried out by energy dispersive spectrometry (EDS).

The relative grindability index of samples was calculated with Equation (1), where:

- K80% (−74 μm) was the relative grindability index of grinding products with −74 μm accounting for 80%;
- $T_{treated}$ was the grinding time of products grinding to a size of −74 μm accounted for 80% with HVEP pretreatment;
- $T_{untreated}$ was the grinding time of products grinding to a size of −74 μm accounted for 80% without HVEP pretreatment.

Samples with a lower relative grindability index K80% (−74 μm) indicates that the samples are higher in grinding efficiency, lower in energy consumption and easier to grind.

$$K_{80\%(-74\ \mu m)} = \frac{T_{treated}}{T_{untreated}} \tag{1}$$

3. Results and Discussion

3.1. HVEP Pretreatment

In order to optimize the operation parameters of the HVEP pretreatment, the experiments with and without HVEP pretreatment were conducted by adjusting the main parameters such as: pulse number, output voltage and electrode gap.

3.1.1. Pulse Numbers

The selected output voltage in the experiment is 30 kV, the electrode spacing is 3 mm, and the influence of pulse numbers of the HVEP pretreatment on the grinding operation is studied under the conditions of 30, 60, 90 and 120, respectively. The effect of the pulse numbers on the grindability of the sample is presented in Figure 5. With an increase in pulse numbers, the mass ratio of broken fine particles with a size of −74 μm presents a clear rising trend at the same grinding time. However, the increase in mass ratio of particles with a size of −74 μm slowed down when further increasing the pulse numbers to be higher than 60. This finding implies that the degree of fine grains fragmentation increased with an increase in pulse numbers. The relative grindability index K80% (−74 μm) decreased from 0.93 to 0.80 when increasing the pulse number from 30 to 120. It indicates that the treated samples are easier to grind compared with untreated samples. Each pulse generated a plasma channel and a set of branching of capillaries in the interfacial area of mineral aggregates, providing necessary conditions for ensuring the efficient liberation of quartz from magnetite minerals. Consequently, it facilitates a substantial generation of the liberated individual mineral particles by the grinding process.

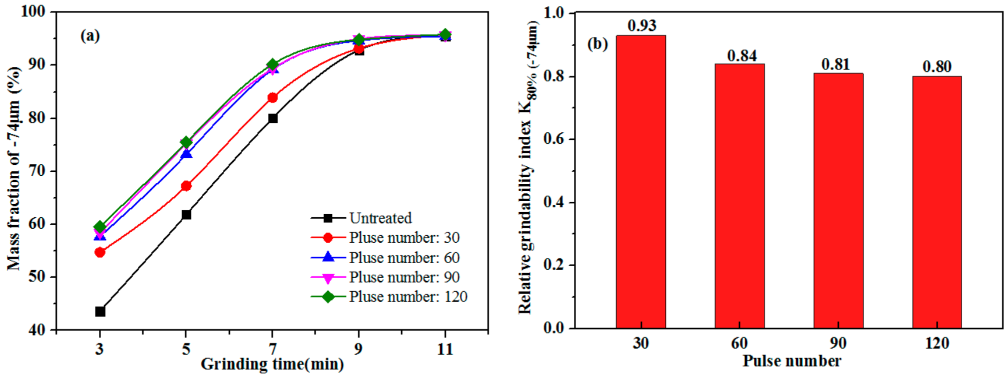

Figure 5. The effect of the pulse numbers on (**a**) mass fraction and (**b**) grindability index.

3.1.2. Output Voltage

The selected electrode spacing in the experiment is 3 mm, the pulse number is 120, and the effect of output voltage of the HVEP pretreatment on the grinding operation was studied under the conditions of 30 kV, 35 kV, 40 kV and 45 kV, respectively. The effect of the output voltage on grindability of the sample is presented in Figure 6. The treated samples by HVEP pretreatment produced more fine particles under the same grinding conditions than the samples. However, no obvious effect of output voltage at different levels on the mass fraction of −74 µm was observed. In order to further study the grindability of the untreated and treated samples, the relative grindability index K80% (−74 µm) was used to measure the influence of different output voltage on the grindability of treated samples. The relative grindability index K80% (−74 µm) increased from 0.80 to 0.82 when the output voltage increased from 30 to 45, which means that the grindability of the treated samples decreased and less fine particles were produced with increasing output voltage.

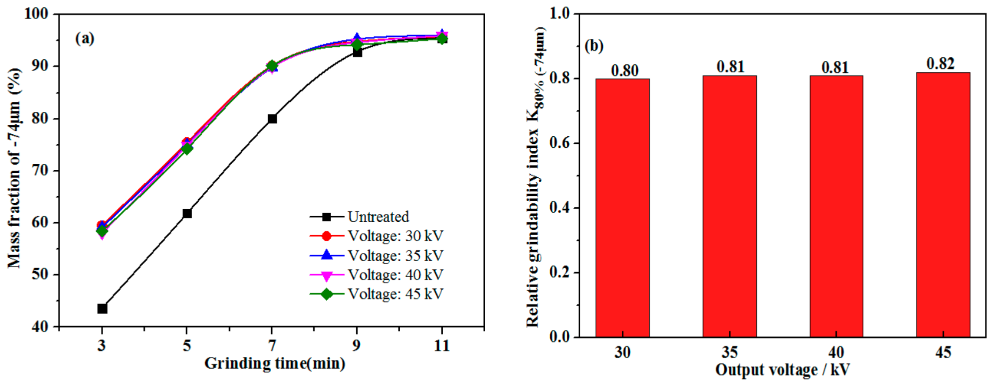

Figure 6. The effect of the output voltage on (**a**) mass fraction and (**b**) grindability index.

3.1.3. Electrode Spacing

The output voltage is 30 kV, the pulse number is 120, and the effect of selected electrode spacing of the HVEP pretreatment on the grinding operation is studied under the conditions of 1 mm, 3 mm, 5 mm and 7 mm, respectively. The mass fraction and the relative grindability index K80%of the untreated and treated sample with a size of −74 µm are illustrated in Figure 7. The mass fraction of treated samples was more than untreated samples at the same grinding conditions, and the particle size of −74 µm in the grinding products of the pretreated products showed a decreasing trend with an increase in the electrode spacing. The mass fraction of −74 µm decreased from 64.75% to 52.70% when the electrode spacing increased from 1 mm to 7 mm at grinding time of 3 min. The reason of these phenomena was that increasing the electrode spacing reduced electric field strength, which subsequently decreased the electric force acting upon the solid aggregates. Another reason could be that the distance between the high-pressure needle electrode and the bottom of breakdown cavity increased, with this part of sample not being subjected to the pretreatment of high-voltage electrical pulses.

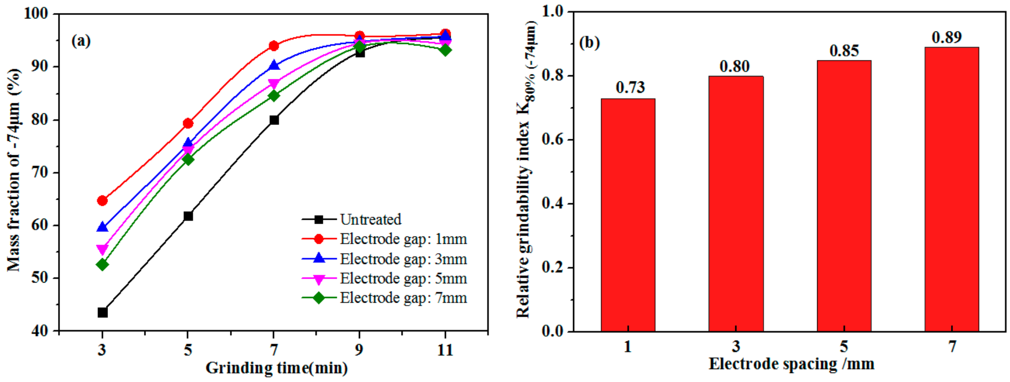

Figure 7. The effect of the electrode spacing on (**a**) mass fraction and (**b**) grindability index.

3.2. Mineral Liberation

The degree of mineral liberation of different particle-size products after grinding was determined, which are illustrated in Figure 8. The pretreated samples are treated under these conditions as follows: the output voltage is 30 kV, the pulse number is 120, the electrode spacing is 1 mm, and the grinding time is 7 min. The untreated samples were ground into powder for 7 min without the addition of high-voltage electrical pulses. As described in Figure 8, the degree of mineral liberation of different particle-size in pretreated samples is higher than that of untreated samples. The degree of mineral liberation of pretreated samples is at least 10% higher than that of untreated samples in the whole size range of each particle size fraction. For example, the degree of mineral liberation in 74~43 μm particle size fraction is 63.96% and 47.10%, respectively, for the treated and untreated samples. The mineral liberation degree of pretreated samples is 13.19% higher than that of untreated samples in the whole size range, which is 43.51% and 56.70% respectively. The ore liberation is commonly achieved based on the difference in mechanical properties of each mineral component of the ore under the action of applied external mechanical forces. With the HVEP pretreatment of the ore, it was possible to cause partial intergranular breakage of magnetite and quartz aggregates. This demonstrates that the grinding processes can benefit from such liberation advancement in obtaining the fully-liberated individual mineral particles.

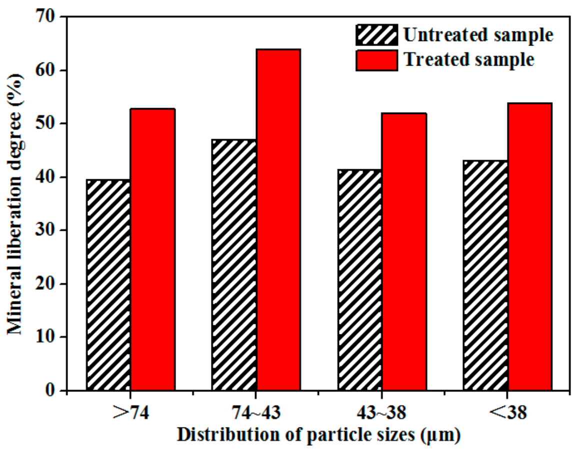

Figure 8. Degree of mineral liberation of samples treated and untreated with HVEP treatment.

3.3. Magnetic Separation

In order to investigate the influence of high-voltage electrical pulses pretreatment on the subsequent magnetic separation, the magnetic separation of samples with and without high-voltage electrical pulses treatment was carried out. The pretreated samples are treated under these conditions the output voltage is 30 kV, the pulse number is 120, and the electrode spacing is 1 mm. The test samples with and without treatments were ground into powder at different times, and the magnetic field intensity was 110 kA/m. The results are presented in Figure 9. It can be seen that the TFe grade of the samples treated with HVEP pretreatment is higher than the untreated samples for the same grinding time. The iron grade increased from 61.06% in the untreated sample to 61.86% in the HVEP treated sample after being grinded for 9 min, the corresponding iron recovery just increased from 82.60% to 83.26%, and the increase of grade and recovery can be achieved with HVEP pretreatment. One possible explanation for this phenomenon was the high percentage of liberated iron mineral particles decomposed from the gangue minerals. The results demonstrated that the HVEP pretreatment is beneficial for the magnetic separation process.

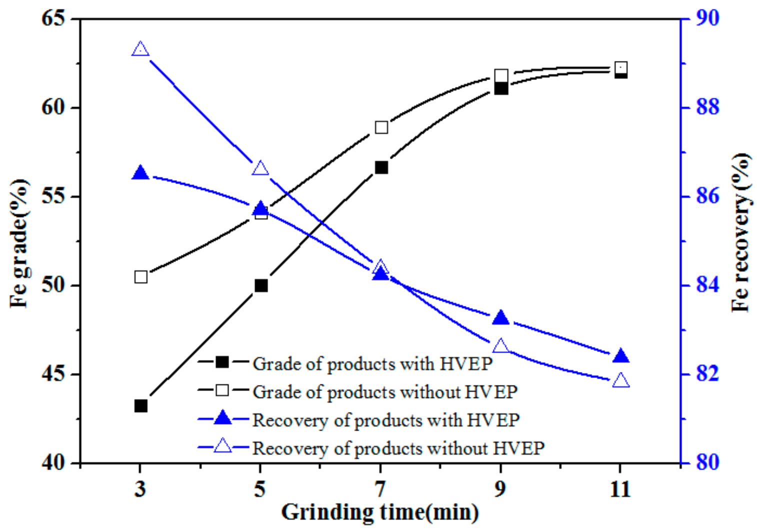

Figure 9. Magnetic separation results of samples treated and untreated with HVEP treatment.

3.4. Microstructures of Samples

The microscopic characteristics were qualitatively analyzed by SEM/EDS from the products with and without HVEP pretreatment, and the results are shown in Figure 10. It was observed from the images that many cracks and microcracks existed within grinding products. The transgranular microcrack propagation was the main form of cracks in the samples under conventional mechanical crushing without HVEP pretreatment as shown in Figure 10a. By contrast, the intergranular microcrack propagation was the main form of cracks in the samples treated with HVEP pretreatment as shown in Figure 10b. The difference between different parameters in the neighboring minerals in the ore aggregates leads to the concentration of the electrical field, and the electrical breakdown takes place throughout the interface of the different minerals in the aggregates. Therefore, the disintegration of shavings develops with the interface of the different minerals. Furthermore, high temperatures existing in the discharge channel were formed at the interface between iron minerals and quartz gangue minerals as presented in Figure 10c. Some minerals in the nearby discharge channel are melted partially, because a part of the electricity is converted into heat energy.

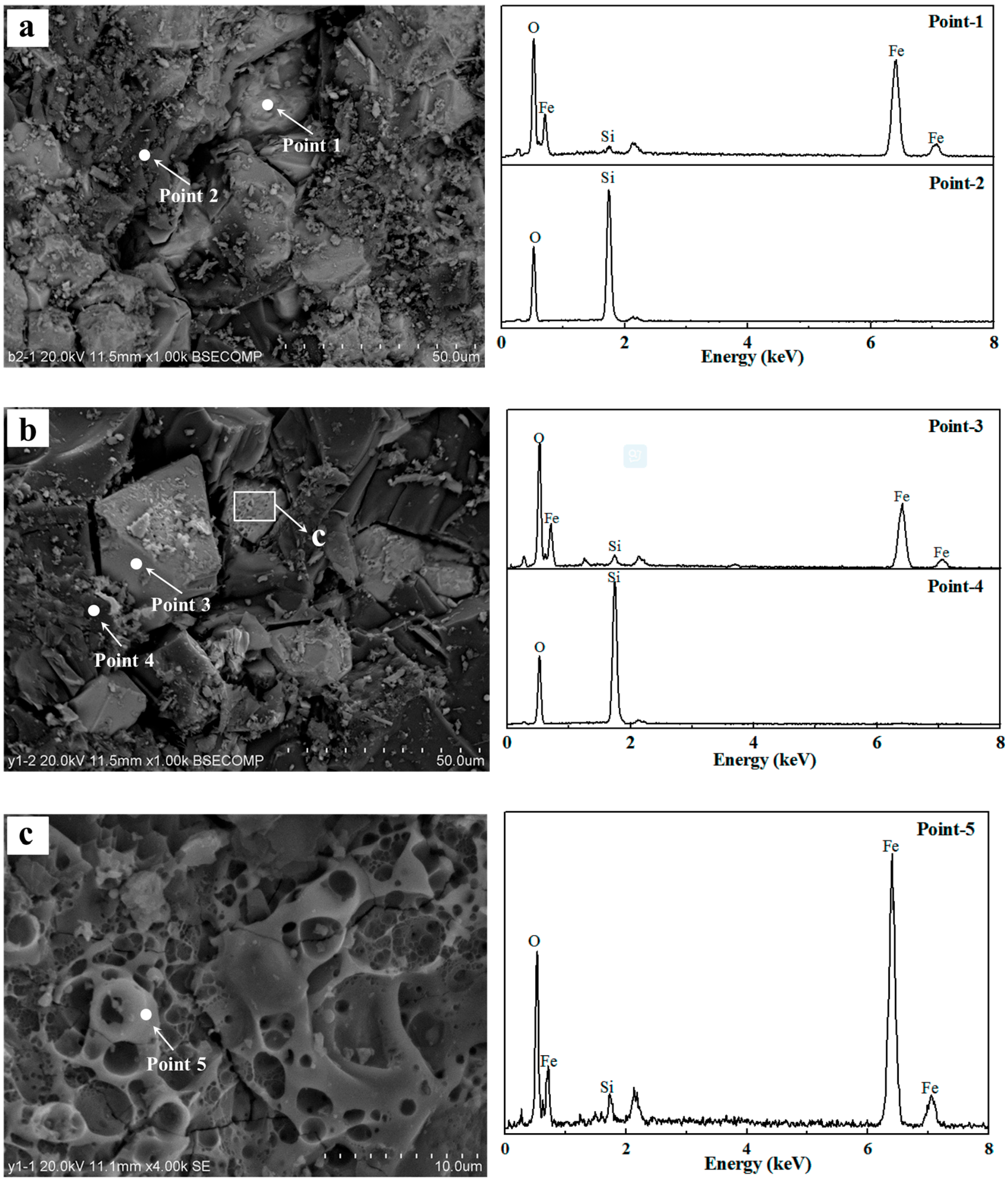

Figure 10. Microstructures of the samples (**a**) untreated and treated (**b**–**c**) with HVEP pretreatment.

4. Conclusions

A comparison of grinding and separation behavior of magnetite ore with and without HVEP pretreatment was carried out. The major findings can be summarized below:

(1) The results showed that more fine particles were produced and the grindability of magnetite ore samples improved by increasing the pulse number, decreasing the output voltage and decreasing the electrode spacing by HVEP pretreatment.

(2) Samples by HVEP pretreatment have higher degree of mineral liberation than samples without HVEP pretreatment in each size fraction; the degree of mineral liberation of pretreated samples is 13.19% higher than that of untreated samples in the whole size range.

(3) The grinding processes and magnetic separation can benefit from liberation advancement in obtaining the fully-liberated individual mineral particles. It is easier and less time-consuming to grind samples treated with HVEP pretreatment, which can also allow us to obtain a higher TFe grade in the magnetic separation.

(4) The morphology characteristics verify that high electrical field intensity is found to occur along the boundaries of two mineral phases and can produce many intergranular microcracks, which also can reduce the grinding time and improve mineral liberation.

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Conflicts of Interest: The authors declare no conflicts of interest.

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