Increased Diamond Recovery from Metasomatically Altered Kimberlite Ores Through the Use of Ultrasonic and Electrochemical Effects in the Sticky Separation Cycle

G P Dvoichenkova¹,², I A Podkamenny¹,², E N Chernysheva³, D B Solovev⁴,⁵
¹Mirny Polytechnic Institute (branch) of North-Eastern Federal University, 678170, 14 Oyunskogo Street, Mirny, Republic of Sakha (Yakutia), Russia
²Institute of Comprehensive Exploitation of Mineral Resources Russian Academy of Sciences, 111020, 4 Kryukovsky Tupik, Moscow, Russia
³LLC “Coralina Engineering”, Bldg. 1, Poslannikov Pereulok 5, Moscow, Russia
⁴Far Eastern Federal University, Engineering school, Vladivostok, Russian Federation
⁵Vladivostok Branch of Russian Customs Academy, Vladivostok, Russian Federation

E-mail: mirniy.yuriy@mail.ru

Abstract. The structural features of mineral formations on hydrophilic diamond crystals lost in the separation process on sticky tables are investigated. A combined electrochemical - ultrasonic technology to increase the efficiency of the separation process on sticky tables during the enrichment of diamond-containing kimberlites is proposed.

1. Introduction
The experience of the concentration plants processing modified kimberlite ores showed that the main losses of diamonds are represented by crystals with a grain size of -5 mm, which make up more than 15% of the cost of marketable products. In standard technological schemes for processing kimberlite ores, diamonds of this size are extracted, as a rule, by sticky and foam separation methods, the effectiveness of which is sharply reduced due to the formation of hydrophilic films on the crystal surface, the formation and fixing mechanism of which is determined primarily by the mineralogical composition of the processed kimberlites [1].

2. Targets of research
To extract diamond crystals of the specified size in the beneficiation and finishing operations of diamond-containing products, sticky separation is used, using the natural hydrophobicity of the surface of diamonds. The main reason for the reduction in technological indicators of sticky separation is the high loss of crystals with tail products of the process, which is caused by hydrophilization of the surface of natural diamonds due to the formation of mineral formations on it upon contact with kimberlites, which underwent active hypergene changes in the conditions of occurrence of deposits. The ore material of the deep horizons of the kimberlite deposits of Western Yakutia is the most altered [1-4], and sticky separation is the final stage in the technology of their processing in processing plants. Loss of diamonds of this class in these conditions is irrevocable.
3. Research methods and techniques

Comprehensive studies were carried out by IR spectroscopy and x-ray methods for analyzing the surface composition of diamonds, electron microscopic studies of the composition and topography of diamond crystals, chemical analysis of the liquid phase and enrichment products, laboratory technological tests of the processes of ultrasonic processing of pulp and electrochemical conditioning of water, mathematical planning and processing of results experiments. The choice of parameters for the electrochemical treatment of circulating water was carried out based on the task of maintaining the ability to dissolve carbonate minerals of polymineral hydrophilizing formations. The results of experiments performed on a laboratory bench show that with a diaphragm-free electrochemical treatment of the circulating water of the above composition for 1-1.5 min at an electric energy consumption of 0.75 - 1.5 kW*h/m³, its ability to dissolve carbonate minerals with the index Riesner is more than 6.85, the power of the ultrasonic field in the working zone is 7.5 W/cm² with a processing time of 1 minute [2].

4. Discussion of findings

The results of the complex of theoretical studies of the geological and hydrogeological conditions of occurrence of the considered kimberlite pipes have established a high degree of secondary transformations of the main kimberlite minerals, due to the contact of the host rocks and highly mineralized underground water systems, as a result of which minerals appear in the system under consideration, causing the formation of hydrophilic films on the diamond surface - oxides iron, magnesium, calcium, etc. (Figure 1), due to which reduced diamond recovery by sticky separation.

Figure 1. Electronic image of the surface of a diamond with a hydrophilic film - a, spectrogram of a mineral hydrophilic film on a diamond surface – b.

Common to all samples of altered kimberlite rocks is the presence in their composition of clay minerals with smectite packets: Na-smectite, mixed-layer talc-smectite and chlorite-smectite. Particles of these minerals, as a rule, are concentrated in finely dispersed slurry products of kimberlite ore processing and have a free charge, which makes them surface-active, as well as capable of cation exchange and interaction with the crystal surface, as a result of which their natural hydrophobic properties and extraction are reduced.

Studies have established [3, 6] that on the surface of unrefined diamonds contained in the tail products of sticky separation, there is a significant amount of hydrophilic formations containing clay minerals having a calcium-magnesium-silicate-carbonate composition with significant amounts of iron and sulfur (Figure 2). Sodium and chlorine are practically not detected, which indicates the non-participation in the structure of the considered slurry formation of halite or calcium chloride. This composition corresponds to the diagnosed elemental composition of sludge classes of samples of
hydrothermally altered kimberlites, which are characterized by a large mass fraction of silicon and less calcium.

![Figure 2](image_url)  
*Figure 2.* Electronic images and X-ray spectra of talc-smectite (a) and serpentine-carbonate (b) formation on a diamond surface.

Surface formations are characterized by the presence of aggregates of sludge classes of rock-forming minerals with pronounced either hydrophobic or hydrophilic properties.

A frequently encountered type of surface formation is rather large slurry grease (conglomerate) of talc-smectite composition or calcium-magnesium-aluminosilicate composition [7-12].

The revealed structural features of mineral formations are characteristic of hydrophilic diamond crystals lost in the processes of sticky separation.

A promising way to remove hydrophilizing formations from the surface of diamonds is a combination of electrochemical and ultrasonic technologies.

Bench tests of the electrochemical method of non-diaphragm electrolysis of mineralized circulating water in the sticky separation cycle were carried out on diamond-containing raw materials of Kimberlite pipes in Western Yakutia in the scheme of dressing plants of Mirny Mining and Processing Plant [13-14]. As the test results showed, such a scheme provides an increase in diamond recovery in sticky separation from 4.3 to 8.1%. During the tests, it was found that the electrochemical treatment of the circulating water modifies its properties to parameters, the values of which partially destroy the mineral formations on the surface of diamond crystals and prevent their re-formation [15-17].

However, the use of the electrochemical method of modifying the surface of diamond crystals is most effective for removing thin-layer films of secondary technogenic hydrophilization.

In view of this fact, subsequent studies were aimed at further improving the efficiency of the sticky separation process and set the task of developing a combined technology that provides for the use of ultrasonic pulp processing along with electrochemical conditioning of water, which removes massive (embossed) hydrophilizing surface formations having conglomerate structure from the mineral surface grains of rock minerals of thin classes differing relatively strong (adhesive) adhesion to the surface of the diamond and not removed when processing the pulp in mechanical devices.

The reason for the effectiveness of the additional application of ultrasonic technology is the combination of cavitation and hydrodynamic effects (acoustic flows and sound-capillary effects) on macro-sized objects ($10^{-2} - 10^{-3}$ cm), comparable with the wavelength ($10^{-2} - 10^{-4}$ cm) of ultrasonic radiation (Figure 3). It should be noted that the combined use of ultrasonic and electrochemical technologies allows not only to destroy hydrophilizing surface formations, but also to prevent their re-fixing on the diamond surface.
Figure 3. Schematic diagram of cleaning the surface of diamonds (1 - film formation; 2 - single sludge grains; 3 - relief formation): a – products of electrochemical conditioning of aquatic environments; b – with the combined action of electrochemical and ultrasonic treatment products.

As shown by the results of enlarged bench tests, the use of ultrasonic processing of diamond-containing ore pulp together with the use of electrochemical conditioning of circulating water can reduce diamond losses in the sticky separation operation by 18.6% (Table 1).

Table 1. Technological indicators of sticky separation during the testing of the combined technology for the restoration of hydrophobicity of diamonds.

| Sample Name                          | Mode (using electrochemical conditioning of circulating water) | Diamond content in tails, conventional units |
|--------------------------------------|---------------------------------------------------------------|---------------------------------------------|
| Tails of sticky separator in class -6+1mm | No ultrasonic treatment                                      | 35                                          |
| Tails of sticky separator in class -6+1mm | With ultrasonic treatment                                    | 43                                          |

Technological indicators of sticky separation, during the testing of the combined technology for the restoration of hydrophobicity of diamonds from tailings samples in the -6 + 1 mm class, where the diamond content amounted to 35 conventional units without ultrasonic processing and 43 conventional units with ultrasonic processing.

5. Conclusion
Hydrophilizing surface formations on diamonds extracted from the kimberlite pipes of Western Yakutia subject to the most significant hypergene changes are mainly represented by sludge-carbonate slurry adhesives fixed on the hydrophilized surface of diamonds and are characterized by significant pore volumes filled with the aqueous phase.
The obtained results showed the promise of the developed combined technology for increasing the efficiency of the sticky separation process in the enrichment of intensively changed diamond-containing kimberlites, and can provide an 18.6% reduction in diamond losses in the sticky separation operation.

References
[1] Podkamennyi I A, Dvoychenkova G P, Kovalchuk O E 2019 Experimental substantiation of the relationship between the structural and chemical properties of mineral formations on natural diamonds and the composition of kimberlite ore IMPC 2018 - 29th International mineral processing congress Canadian Institute of Mining, Metallurgy and Petroleum pp 4083-4092
[2] Spetsius Z V, Cliff J, Griffin W L, O'Reilly S Y 2017 Carbon isotopes of eclogite-hosted diamonds from the Nyurbinskaya kimberlite pipe, Yakutia: The metasomatic origin of diamonds Chemical Geology vol 455 pp 131-147
[3] Agrosi G, Nestola F, Tempesta G, Bruno M, Scandale E, Harris J 2016 X-ray topographic study of a diamond from Udachnaya: Implications for the genetic nature of inclusions Lithos vol 248-251 pp 153-159
[4] Wang J, Wan L, Hao S, Chen J 2017 Surface modification of diamond and its effect on the mechanical properties of diamond epoxy composites Science and Engineering of Composite Materials vol 24 2 pp 271-278
[5] Podkamennyi I A 2019 Increased diamond recovery under sticky separation based on combined electrochemical and ultrasonic treatment Abstract for the degree of Ph.D. (Moscow) Institute of Comprehensive Exploitation of Mineral Resources Russian Academy of Sciences
[6] Trofimova E A, Zuev A V, Dvoichenkova G P, Bogachev V I 2000 Efficiency of application of membraneless electrochemical water treatment in the processes of enrichment of diamond-containing kimberlites Development of the ideas of I. N. Plaksin in the field of mineral enrichment and hydrometallurgy (M.: Mining Institute named after A.A.Skochisky) 327 p
[7] Dvoichchenkova G P, Minenko V G, Kovalchuk and others O E 2012 Intensification of the process of froth separation of diamond-containing raw materials based on the electrochemical method of gas saturation of water systems Mining Journal 12 pp 88-92
[8] Chanturia V A, Goryachev B E 2008 Enrichment of diamond-bearing kimberlites Progressive technologies of the comprehensive processing of mineral raw materials Edited by V A Chanturia (M.: Publishing house "Ruda i metally (Ore and Metals)") pp 151-163
[9] Chanturia V A, Trofimova E A, Dikov Yu P, Dvoichenkova G P, Bogachev V I, Zuev A A 1998 The relationship of surface and technological properties of diamonds in the enrichment of kimberlites Mining Journal 11 - 12 pp 52-56
[10] Kulakova I I 2004 Chemistry of nanodiamond surfaces Physics of the Solid State vol 46 Ed. 4 pp 621–628
[11] Chanturia V A, Trofimova E A, Dvoichenkova G P, Bogachev V I 2010 Mineral and organic nano-formation on natural diamonds: Conditions of their formation, methods of their removal Mining Journal 7 pp 68-71
[12] Chanturiya V A, Dvoichenkova G P, Kovalchuk O E, Kovalenko E G 2013 Change in the technological properties of diamonds under the conditions of processing the secondarily altered kimberlites Rudy i Metally 3 pp 48 – 55
[13] Chanturiya V A, Dvoichenkova G P, Kovalchuk O E, Trofimova E A 2015 Features of the composition of the surface of hydrophilic diamonds and their role in the process of froth separation Physico-technical problems of the development of mineral resources 6
[14] Dvoychenkova G P 2014 Mineral formations on the surface of natural diamonds and the method of their destruction on the basis of electrochemically modified mineralized waters Physico-technical problems of the development of natural resources 4 pp 159-171
[15] Maksimovsky E A, Fayner N I, Kosinova M L, Rumyantsev Yu M 2004 Investigation of the structure of thin nanocrystalline films Structural chemistry journal T 45
[16] Goryachev B E 2010 Technology of diamond-bearing ores processing (M: MISiS) 326 p
[17] Kulakova I I 2004 Chemistry of nanodiamond surfaces *Physics of the Solid State* vol 46 Ed. 4 pp 621 – 628