Role of radiation modification in ore pretreatment

VI Rostovtsev
Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: benevik@misd.ru

Abstract. It is found that the increased radiation exposure of rocks treated by accelerated electrons changes the rock deformation and strength characteristics: ultimate compression strength as well as moduli of deformation and elasticity. The uniaxial compression strength of granite is 68.33 MPa without treatment and 35.08 MPa at the absorbed radiation dose of 10 kGy. The established possibility of weakening of rocks by accelerated electrons can be used to reduce consumption of electricity during ore pretreatment and to minimize loss of useful components in processing.

1. Introduction
The present-day development in the mineral mining and processing industry is connected with treatment of rebellious ore and mine waste. This trends conditions also high loss of commercial components at the stages of mining and beneficiation, as well as considerable operating and capital cost of final output.

Up to 35–40% of loss of valuable components in pre-treatment is connected with mineral aggregates and 30–35%—with fines smaller than 10 μm in size [1]. In order to reduce such losses in processing finely disseminated ore without formation of aggregates and over-grinding, conventional crushing and milling in jaw and cone crushers and ball mills should be replaced by selective disintegration. The process of disintegration is the main operation in ore pretreatment. Ore is assumed prepared for dressing when ground to a certain size. As per the coarseness standard adopted in Russia and in the CIS countries, processing of nonferrous and ferrous metal ore accepts size grades of –71 and –44 μm. Some foreign processing plants admit size –38 μm. In recent years, low-grade and uneconomic ore treatment as well as recovery of finely dispersed minerals and pure metals is carried out using equipment of fine (smaller than 20 μm) and super-fine (smaller than 7 μm) milling [2]. Energy inputs are comparatively low at the stages of crushing (to 1.2 kW·h/t) and high at the stages of milling (50 kW·h/t).

The problem has been complicated of later decade as processing increasingly involves rebellious finely disseminated and low-grade ore, and target components are over-ground and lost with slurry in this case. Mineral crystals of many studied and extracted nonferrous metal ore and tin, rare ad rare earth elements are within the size range of 0.015–0.050 mm, and the task of ore pretreatment consists in provision of the above-mentioned coarseness of particles with preservation of the crystal structure of minerals.

2. Different approaches to mineral processing
The commonly used ball mills are low-efficient with the identified ore types due to increased sliming and destruction of useful minerals, which impairs selectivity. In longer period milling, amount of mineral association of higher mechanical strength grows; nondecomposed aggregates in such associations are
30–40 μm in size, and their disintegration requires higher impact effects. The analysis of many studies in the sphere of geomaterial grinding makes it possible to state that fine and super-fine milling requires equipment with much higher energy of crushing than in ball mills using acceleration of gravity [3, 4].

The process properties depend on the constitution and genesis of minerals, which governs property contrast of intergrown minerals, their changeability under various effects. The maximum information on composition and structural parameters of minerals under processing can be obtained from the data of process mineralogy. The interactions of minerals and their grain size distribution condition coarseness of disintegration and dissociation ability of minerals under treatment.

In order to reduce mineral loss and energy consumption, it seems promising to treat rebellious minerals by nonmechanical energy deposition that enables overcoming physical intractability and allows selective disintegration without over-grinding [1, 7–10]. High efficiency of energy treatment techniques in mineral dressing is proved by researchers of foreign scientist from Canada, Germany, Japan, South Africa, etc.

The distinguished Russian scientists, Corresponding member of the USSR Academy of Sciences I. N. Plaksin assumed one of the critical trends in mineral processing is such energy deposition that improves completeness and multi-purposiveness of mineral use. He was one of the pioneer researches to justify efficiency of external actions in mineral dressing processes [11].

In this fashion, the problem connected with maximum dissociation of minerals at the minimum over-grinding can be solved through engineering innovative machines [1, 2, 4, 12], or by intensification of available procedure by means of using energy deposition [1, 7, 13]. The review of the studies accomplished by some institutions, including the Chinakal Institute of Mining [8, 9] reveals possibility of improving dissociation of rebellious minerals and enhancing processing efficiency by means of preliminary treatment by accelerated electron flow. According to the analysis of mineral samples from different deposits, they are as a rule polymetallic and represented by rock-forming minerals and rocks, for example, limestone, hornfel and granite. The aim of this study was to examine the change in strength of core specimens of the listed rock types as a result of treatment by high-energy electrons.

Limestone is one of the widest spread sedimentary rocks. Limestone deposits make 19–22% of all sediments. Regarding occurrence in the earth crust, limestone is the third after quartz and feldspar. Large quantity of calcite deposits from hot water in hydrothermal veins with sulphides and in effusive rock amygdales with zeolite, chalcedony, quartz and barite.

Hornfel strata enclose copper–molybdenum formations containing copper, molybdenum, gold, silver, lead, zinc, cobalt, bismuth and mercury (Endybai deposit in Yakutia); antimony (Terek in Kirgizia, Xikuangshan in China); tungsten (Tigrinoe in Primorye) and other metals and minerals. Granite is the most important rock is the earth crust. Granite is tightly connected with the deposits of such minerals as Sn, W, Mo, Li, Be, B, Rb, Bi, Ta and Au.

The physical and mechanical properties of minerals and rocks were determined using core samples of regular cylindrical shape in accordance with the effective standards and procedures, on equipment passed metrological certification. The samples had a diameter $d$ of 30 mm and height $h$ of 60 mm; the geometry factor $h / d$ was 2 upon average for the tested samples, which complied with the Russia’s State Standard 21153.2-84. Deformability testing procedure agreed with the requirements [14–16]. The prepared core samples were exposed to beam of accelerated electrons on industrial electron accelerator ILU-6 at the Institute of Nuclear Physics, SB RAS, under electron energy of 2 MeV. The key research findings on the effect of electron treatment on the mechanical and acoustic properties of ore samples are presented in Tables 1 and 2 and in the figure.

It follows from the data in Table 1 that treatment by the beam of accelerated electrons changes mechanical properties of limestone, hornfel and granite core samples. The increase in the absorbed dose results in the decrease in compression strength, as well as in deformation and elasticity moduli. Limestone has the compression strength of 49.11 MPa before treatment and 35.24 MPa after absorbing a dose of 15 kGy. Poisson’s ratios grow with the absorbed dose: 0.17 before treatment and 0.38 after absorbing the dose of 15 kGy. The same laws are observed in hornfel and granite.
Table 1. Results of mechanical and dynamic testing of limestone, hornfel and granite core samples after accelerated electron treatment.

| Sample No. | Absorbed dose, kGy | Sample size $d \times h$, mm | Mechanical properties | Static elastic characteristics |
|------------|---------------------|-----------------------------|----------------------|-------------------------------|
| Limestone ($\rho = 2.68 \text{ g/cm}^3$) | | | Compression, strength $\sigma$, MPa | Uniaxial compression, modulus $E$, GPa | Poisson’s ratio $\nu$ |
| 0 | 0 | 29.5x60.2 | 49.11 | 13.20 | 0.17 |
| 5 | 5 | 29.5x60.5 | 76.61 | 13.32 | 0.22 |
| 10 | 10 | 29.5x60.5 | 38.24 | 7.44 | 0.26 |
| 15 | 15 | 29.5x60.4 | 35.24 | 10.43 | 0.38 |
| Hornfel ($\rho = 2.66 \text{ g/cm}^3$) | | | | | |
| 0 | 0 | 29.5x60.3 | 123.15 | 29.70 | 0.175 |
| 5 | 5 | 29.4x60.3 | 115.20 | 22.72 | 0.18 |
| 10 | 10 | 29.4x60.3 | 78.97 | 9.71 | 0.18 |
| 15 | 15 | 29.5x60.2 | 135.89 | 28.64 | 0.19 |
| Granite ($\rho = 2.45 \text{ g/cm}^3$) | | | | | |
| 2 | 0 | 29.5x61.3 | 68.33 | 13.19 | 0.19 |
| 5 | 5 | 29.6x60.9 | 67.98 | 9.34 | 0.19 |
| 8 | 10 | 29.6x60.0 | 35.08 | 7.04 | 0.16 |
| 9 | 15 | 29.6x60.0 | 57.53 | 10.34 | 0.20 |

Table 2. Acoustic properties of limestone, hornfel and granite core samples after accelerated electron treatment.

| Sample No. | Absorbed dose, kGy | Sample size $d \times h$, mm | Atmospheric conditions | Deformation modulus $E$, GPa | Poisson’s ratio $\nu$ |
|-------------|---------------------|-----------------------------|----------------------|-------------------------------|-------------------------------|
| Limestone ($\rho = 2.68 \text{ g/cm}^3$) | | | Wave velocity, m/s | P-wave | S-wave |
| 0 | 0 | 29.5x60.2 | 5021 | 2657 | 49.30 | 0.31 |
| 5 | 5 | 29.5x60.5 | 4605 | 1992 | 29.50 | 0.38 |
| 10 | 10 | 29.5x60.5 | 4386 | 1992 | 29.21 | 0.37 |
| 15 | 15 | 29.5x60.4 | 4485 | 1982 | 28.62 | 0.38 |
| Hornfel ($\rho = 2.66 \text{ g/cm}^3$) | | | | | |
| 0 | 0 | 29.5x60.3 | 5601.3 | 3030.7 | 63.62 | 0.29 |
| 5 | 5 | 29.4x60.3 | 5339.7 | 2972.7 | 60.62 | 0.28 |
| 10 | 10 | 29.4x60.3 | 5345.7 | 3012.0 | 61.81 | 0.27 |
| 15 | 15 | 29.5x60.2 | 5233.3 | 2971.3 | 59.52 | 0.26 |
| Granite ($\rho = 2.45 \text{ g/cm}^3$) | | | | | |
| 2 | 0 | 29.5x61.0 | 3747 | 2287 | 32.01 | 0.20 |
| 5 | 5 | 29.6x56.9 | 3543 | 2142 | 30.29 | 0.27 |
| 8 | 10 | 29.6x60.0 | 4054 | 2376 | 37.98 | 0.26 |
| 9 | 15 | 29.6x60.0 | 3905 | 2339 | 37.49 | 0.26 |
The tests show the change in acoustic properties of limestone, hornfel and granite after radiation exposure (Table 2). In an initial core sample of limestone, velocities of P- and S-waves are, 5021 and 5021 and 2657 m/s, respectively, these parameters after absorption of the dose of 15 kGy are 4485 and 1982 m/s. The P- to S-wave ratio is on average 2.14 under atmospheric conditions. This ratio in limestone core sample is 2.2–2.3 after treatment by accelerated electrons and 1.89 before treatment. In case of hornfel tests, it is observed that the ratio of P- and S-waves reduces when the dose of radiation is increased.

Regarding granite (Table 2), it is seen that with an increase in the absorption dose to 15 kGy, velocities of P- and S-waves first decrease and then increase. P- and S-wave velocities are 37478 and 2287 m/s in the initial core sample of granite, 3543 and 2142 m/s after absorption of the dose of 5 kGy and 3905 and 2339 m/s after exposure to the radiation dose of 15 kGy.

It follows from the data in Tables 1 and 2 that the change in the deformation and strength characteristics of granite is connected with the modification of its structure after treatment by accelerated electrons. The same inference is drawn after examining specimens in the figure. Uniaxial compression of granite specimen treated by accelerated electrons results in more particles as compared with the untreated specimen. In case of limestone, two particles are obtained in failure of untreated specimen and from 6 to 10 particles in disintegration of the treated specimen. Thus, the integrated analysis of deformability and strength characteristics of core specimens of different rocks show that treatment of the specimens by the high-energy electrons changes mechanical, dynamic and acoustic characteristics of rocks: uniaxial compression strength, elasticity modulus, P- and S-wave velocities.

The behavior of limestone, hornfel and granite in failure after treatment by accelerated electrons is connected with the specific nature of interaction between electrons and solids [8, 17]. A beam of electrons generates point defects in minerals in short time of \( \sim 10^{-11} \) s: equal number of vacancies and dislocated atoms appear during this period. The equilibrium is achieved by formation of constant clusters or disappear of unstable damages under diffusion transfer. Then, the vacancies reach peak concentrations and merge into caverns that become places of discontinuities in solid material. As a result, displacement of dislocations is simplified and failure of minerals is intensified.

3. Conclusions
Finally, mechanical properties of minerals are changed under treatment of accelerated electrons. Caverns, electric breakdown and accumulation of dislocation along the boundaries result in the micro-cracking and mechanical instability. The revealed weakening of different rock types under influence of
accelerated electrons can be used to reduce power consumption in ore pre-treatment and to minimize loss of commercial components in the subsequent processing circuits.

Acknowledgements
This study was accomplished in the framework of R&D No. AAAA-A17-117092750073-6.

References
[1] Chanturia VA and Kozlov AP 2017 Contemporary issues of comprehensive processing of refractory ores and technogenic materials Plaksin’s Readings–2017: International Conference Proceedings Krasnoyarsk: SFU pp 3–6 (in Russian)
[2] Chanturia VA and Malyarov PV 2012 A review of worldwide achievements and development prospects of the disintegration technology in mineral processing Plaksin’s Readings–2012: International Conference Proceedings Petrozavodsk: KNTs RAN pp 3–10 (in Russian)
[3] Revnivtsev VI, Gaponov GV, Zarogatsky LP et al 1988 Selective Disintegration of Minerals Moscow: Nedra (in Russian)
[4] Vaisberg LA and Zarogatskii LP 2003 Foundations of optimal mineral disintegration Journal of Mining Science Vol 39 No 1 pp 87–93
[5] Kotova OB, Ozhogina EG and Rogozhin AA 2017 Applications of mineralogy in the refractory mineral processing technology Plaksin’s Readings–2017: International Conference Proceedings Krasnoyarsk: SFU pp 10–13 (in Russian)
[6] Pirogov BI 2017 Nature and evolution of the process properties of minerals Plaksin’s Readings–2017: International Conference Proceedings Krasnoyarsk: SFU pp 28–31 (in Russian)
[7] Chanturia VA and Bunin IZh 2007 Non-traditional high-energy processes for disintegration and exposure of finely disseminated mineral complexes Journal of Mining Science Vol 43 No 3 pp 311–330
[8] Bochkarev GR et al 1997 Prospects of electron accelerators used for realizing effective low-cost technologies of mineral processing Proceedinds XX International Mineral Processing Congress Aachen: Clausthal-Zellerfeld Vol 1 pp 231–243
[9] Kondrat’ev SA et al 2014 Justification and development of innovative technologies for integrated processing of complex ore and mine waste Journal of Mining Science Vol 50 No 5 pp 959–973
[10] Chanturia VA, Trubetskoy KN, Viktorov SD and Bunin IZh 2006 Nanoparticles in Processes of Disintegration and Disclosure of Earth Materials Moscow: IPKON RAN (in Russian)
[11] Plaksin IN., Shafeev RS, Chanturia VA and Yakushkin VP 1970 On the effect of ionizing radiation on the flotation properties of minerals Concentration of Minerals: Selected Works IN Plaksin (Ed)Moscow: Nauka pp 292–300 (in Russian)
[12] Revnivtsev VI 1977 Research and development problems in the improvement of the ore preparation technology Obog. Rud No 6
[13] Chanturia VA 2008 Sustainable development prospects of the mineral processing industry in Russia Advanced Technology for Comprehensive Mineral Processing VA Chanturia (Ed) Moscow: Ruda Metally (in Russian)
[14] RF State Standard GOST 28985-91 Rocks. Methods for Determining Strain Properties under Uniaxial Compression
[15] RF State Standard GOST 21152.2-84 Rocks. Uniaxial Compressive Strength Measurement Methods
[16] RF State Standard GOST 21153.7-75 Rocks. Measurement Method for Elastic P- and S-Wave Propagation Velocity
[17] Kovalev AT 1999 Possibility of applying radioactive electrization for electrical separation of pulverized mineral mixture Journal of Mining Science Vol 35 No 2 pp 199–203