Radiation-Thermal Treatment in Ore Dressing

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Abstract. The radiation-thermal electron beam treatment of ore concentrates and its influence on the useful fractions yield are described.

1. Introduction

During the past 25 years the mankind did not discover a single new considerable metalliferous deposit containing iron, lead-zinc, copper-nickel, tin or complex ores. Of late years the metals are obtained from the ores having complex material constitution and characterized by low dressability, low metal content, fine dissemination and similar surface properties of the minerals and barren rocks.

The future mankind welfare will depend on the increase in efficiency and all-inclusiveness of the ores treatment.

The electric energy consumption for ore dressing and pretreatment is about 10% of the total energy generated in the world. The Russian mining industry share in the gross domestic product is about 30%.

These are the basic facts for estimation of the potential benefits if the new more efficient technologies in ore dressing will be developed. The prominent Russian scientist I.N. Plaksin considered that one of the main directions in the ores treatment is the search for such energy depositions that will sufficiently increase the complexity and completeness of the useful components recovery. He was one of the pioneers who substantiated external actions efficiency in the ore dressing processes [1].

The studies [2-7] shows that preliminary (before grinding) electron beam treatment of the ores or electron beam treatment of the concentrates is an efficient instrument for mechanical and physical-chemical properties modification.

The electron beam treatment activates the surface and volumetric physical-chemical processes in minerals and ores resulting in their weakening and floatation properties changing. This treatment can also augment the magnetic properties of ferriferous sulphides [5].

The processes caused by electron beam greatly depend on the surface current density and total absorbed dose. At low current densities and low dose (less than 1 kGy) the main effect is radiation defects formation without noticeable changes in physical properties of the treated matters.

Absorbed dose range 1-10 kGy is characterized by electric charge accumulation and following electric discharges. The electric charge is not accumulated in conductive minerals (pyrite, galenite, etc.). In the non-conductors (quartz, sphalerite, etc.) the electric charge is accumulated until the electric strength threshold will be reached, and then the electric discharge happens forming the breakdown paths. After discharge the process repeats, and the breakdown paths can grow. The charge pulsations and discharges are followed by mechanical tension pulsations. The tension pulsations and
breakdown paths cause the microcracks formation and growing causing minerals weakening [6]. The pulse electron beam is more efficient for these processes than the continuous electron beam.

The ore particles usually consist of the heterogeneous materials, and the breakdown paths and microcracks are usually forming and developing in the crystallite coalescence regions. The result is the following selective disintegration and increase in grinding rate process.

The high absorbed doses (of more than 100 kGy) get by intensive electron beam without forced cooling simultaneously heat the treated matters during the irradiation. The combined high temperature and irradiation action (radiation-thermal process) causes the physical-chemical processes to go differently than in the purely thermal process.

We have studied the radiation-thermal processes in some ferriferous sulphide minerals and their influence on the following concentrations process.

2. Magnetic separation and radiation-thermal treatment

The magnetic separation is widely used for extraction of the magnetic and weak-magnetic minerals from the ferriferous and other ores. It bases on the differences in magnetic properties of the different grinded ore components. This technology is easy in realization, highly efficient and ecologically friendly because it does not pollute the environment.

But the differences in magnetic properties of the minerals are usually not enough large for their efficient separation, especially for weak-magnetic iron ores. To improve the ore concentration process it is necessary to increase the magnetic properties differences by physical, physical-chemical and even by chemical effects.

A calcining at high temperature and certain conditions (oxidizing, neutral or reducing medium) converts the weak-magnetic ferriferous minerals into magnetic compounds (magnetite Fe₃O₄, hematite Fe₂O₃ or γ-hematite Fe₂O₃). This is the main industrial process used for modification of the ores’ magnetic properties. Process temperature is 600°C and higher, process duration – 4-6 hours or more. Main problems of the process – high power consumption, long duration, high cost and air pollution.

The phase transitions induced by electron beam treatment are well known for decades. Our studies have shown that the treatment by intensive electron beam can modify the magnetic properties of the weak-magnetic minerals [8]. It is important for ore dressing intensification and minerals separation.

We have experimentally studied the radiation-thermal modification of some ferriferous sulfide minerals. The treatment carried out in the Budker Institute of Nuclear Physics, Novosibirsk, by pulse electron accelerator ILU-6, electron energy was 2.4 MeV. The pulse beam current was usually set to 320 mA, pulse duration was 0.5 ms, pulse repetition frequency was varied to control the average beam current and respectively the dose rate. The maximum beam power of this ILU-6 machine is 12.5 kW, so the beam power is enough to heat the ore samples to the required temperatures up to 600°C and more. (The maximum radiation-thermal process temperature reached on this installation was 1500°C).

The ore samples temperature can be monitored by the chromel-alumel thermocouples in the chosen points – 4 channels are envisaged. The process temperature displayed in the special window of the accelerator control program. The special accelerator program unit permits to control and stabilize the temperature of the treated samples according the preset temperature chart.

Various ferriferous crushed ores were placed under the accelerator beam window and treated in the atmosphere, see Figure 1.
Figure 1. Ore samples under ILU-6 accelerator beam window

The minerals’ magnetic properties were assayed by specific magnetic moment measured by vibrating-coil magnetometer LDJ9600 (LDJ Electronic Inc., USA).

The phase transitions after radiation-thermal treatment were studied by X-ray diffraction analysis. The specific magnetic moment values observed after treatment depended on process temperature and mineral fineness.

3. Experimental studies

The pyrite (FeS$_2$), arsenopyrite (FeAsS), chalcopyrite (CuFeS$_2$) and other crushed ores of various finenesses were subjected to radiation-thermal treatment on the ILU-6 accelerator in the temperature range of 300-600°C.

Figure 2 shows the temperature control window of the accelerator control program for one experiment – pyrite treatment with maximum temperature of 400°C and total absorbed dose about 300 kGy. The blue line indicates the preset temperature chart, the red line shows the real temperature during the experiment, the horizontal axis shows the time in minutes. The heating up to 400°C carried out in 5 minutes, then the beam was switched off and sample was cooled due to free convection (without forced cooling).

Figure 2. Pyrite radiation-thermal treatment temperature curve, time in minutes, dose 300 kGy

   Blue line – preset temperature chart
   Red line – pyrite temperature curve
The 5 minutes radiation-thermal treatment at temperature of 400°C greatly augmented the magnetic moments of the pyrite samples:
- Pyrite with fineness of 75-180 micrometers – specific magnetic moment have changed from $0.2\times10^{-8}$ A·m$^2$/g to $10.5\times10^{-8}$, increase in $10.5/0.2 \approx 53$ times.
- Pyrite with fineness of 53-75 micrometers – specific magnetic moment have changed from $0.4\times10^{-8}$ A·m$^2$/g to $18.1\times10^{-8}$, increase in $18.1/0.4 \approx 45$ times.

The difference for arsenopyrite is greater, see it below.

The radiation-thermal treatment increased the magnetic moments depending on the mineral type and fineness (size of the particles) at temperature of 400°C:
- in 53 times for pyrite with fineness of 75-180 micrometers
- in 45 times for pyrite with fineness of 53-75 micrometers
- in 291 times for arsenopyrite with fineness of 53-75 micrometers
- in 921 times for arsenopyrite with fineness of less than 53micrometers
- in 9.7 times for chalcopyrite with fineness of 75-180 micrometers.

The magnetic phases $\text{Fe}_2\text{O}_3$ and $\text{Fe}_3\text{O}_4$ in various combinations were observed after radiation-thermal treatment.

The phase $\text{Fe}_2\text{O}_3$ (as well as $\gamma\text{-Fe}_2\text{O}_3$) has the greater magnetic moment than $\text{Fe}_3\text{O}_4$ phase.

The magnetic properties of the ore samples subjected to radiation-thermal treatment depend on the magnetic phases content as well as on the samples fineness.

X-ray diffraction patterns in Figure 3 show pyrite phase structures before the treatment, after thermal treatment at temperature of 400°C and after radiation-thermal treatment at the same temperature.

![Figure 3. Pyrite (FeS$_2$) X-ray diffraction patterns](image)

- **a** – initial pyrite
- **b** – pyrite after thermal heating up to 400°C
- **c** – pyrite after radiation-thermal heating up to 400°C

**The thermal treatment at temperature of 400°C did not result in magnetic phases formation.**

The low temperature (400°C) nonmagnetic sulphides transition into magnetic compounds was first time observed in pyrite, chalcopyrite and arsenopyrite – it is the radiation-thermal treatment effect.

The temperature threshold for magnetic phase formation in thermal heating process is 600°C, it was confirmed by our experiments. The thermal treatment results in formation of the $\text{Fe}_3\text{O}_4$ phase that has the lower magnetic moment than $\text{Fe}_2\text{O}_3$ and $\gamma\text{-Fe}_2\text{O}_3$ phases.
The advantages of the radiation-thermal pyrite treatment – process temperature can be lower in 200°C, process time is shorter (5 minutes comparing with 4-6 hours), the magnetic moment is greater (due to Fe₂O₃ and γ-Fe₂O₃ phases formation) thus improving the magnetic separation process.

Figures 4 and 5 below show the chalcopyrite and marmatite X-ray diffraction patterns after radiation-thermal treatment at temperature of 600°C and dose of 1000 kGy.

![Figure 4. Chalcopyrite X-ray diffraction pattern after radiation-thermal treatment, temperature 600°C, dose 1000 kGy](image1)

![Figure 5. Marmatite X-ray diffraction pattern after radiation-thermal treatment, temperature 600°C, dose 1000 kGy](image2)
4. Conclusion
The radiation-thermal treatment gave good results – we observed low temperature (400°C) non-magnetic sulphides transition into magnetic compounds. Such low transient temperature was first time observed in pyrite, chalcopyrite and arsenopyrite. The thermal treatment at temperature of 400°C did not result in magnetic phase formation.

The radiation-thermal process completed in 5-10 minutes (for fineness of less than 180 micrometers). The traditional calcining process lasts 4-6 hours at temperature of 600°C or higher.

The magnetic moments after radiation-thermal treatment increased in 9-291 times. The phase content after radiation-thermal treatment get better comparing with the phase content after thermal treatment. Magnetic properties augmentation in ferriferous compounds owing to radiation-thermal treatment offer the challenge to develop the new more efficient and ecologically pure technologies for all-inclusive ore dressing.

Radiation-thermal treatment can increase efficiency and all-inclusiveness of the ores treatment, augment the useful products output and sufficiently decrease the energy consumption due to lower process temperature and shorter treatment time.

The radiation-thermal treatment permits to intensify and to better separate the compounds of tin ores concentrates containing arsenopyrite. About 90% of the ferriferous compounds and 70% of the arseno-compounds can be extracted into the magnetic fraction.

The radiation-thermal treatment can be built into the existing technological schemes with relatively low efforts – there is no need to change the dressing works equipment.

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