Ore of the Tomtor rare-earth deposit for its industrial processing

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Abstract. One of the most promising rare-earth metal (REE) deposits is the Tomtor deposit. The purpose of the work was to study the technological sample of the Tomtor ore deposit to determine the methods of its industrial processing. To achieve this target, studies were conducted on the particle size distribution, mineral and chemical composition of the ore. It was established that the ore of the Tomtor deposit is a fine-disperse material, the particles of which are represented by polymineral aggregates of microcrystals smaller than micrometer. The ore belongs to pyrochlore-monazite-crandallite variety of phosphate-rare-metal ores and is rich in the content of minerals of rare-earth elements. Due to the fine-disperse and high complexity, the ore under this studying cannot be enriched by the traditional methods. An option for processing ore using combined pyro- and hydrometallurgy methods is proposed.

Keywords: Tomtor ore deposit, rare-earth metal (REE), niobium (Nb), particle size distribution.

1. Introduction

The demand for rare-earth metal in various industries is increasing every year. In this regard, the most important area of scientific research is the study of new promising deposits of REE ores for their industrial processing. One of the most promising deposits of REE ores is the Tomtor complex scandium- rare-earth-niobium deposit [1-5]. The practical significance of Tomtor ores is determined by the huge amounts and unique concentrations of niobium (Nb), yttrium (Y), scandium (Sc) and terbium (Tb). By reserves and concentration of REE, it exceeds all known world analogues: the average mass fraction of REE oxides (REO) reaches 8-12 %, including 0.5 % of the most valuable yttrium (III) oxide [6-11]. Tomtor ores also contain high concentrations of niobium (up to 7%). The content of rare-earth metal oxides in the Tomtor ore deposit is 2 times higher than in the richest foreign mountain Pass Deposit in the United States, and the niobium content is 2.5 to 3 times higher than in the richest field in Brazil (Araxa, which provides more than 80% of the world's niobium production). The distribution of REO in the Tomtor ores deposit is shown in figure 1 [12]. The purpose of this work is to study the technological sample of the Tomtor ore deposit to determine the methods of its industrial processing. To achieve the goal of the study, the following tasks were performed:

- Investigation of the particle size distribution, mineral and chemical composition of ore
- Study of the distribution of target ore components by size classes.
Figure 1. Relative mass fraction of REO in Tomtor ore deposit.

2. Materials and methods
The object of research was the sample of ore from the Buranny site of the Tomtor deposit. The work evaluates its technological properties, which is necessary in the future to develop a technology for ore processing. For this purpose, a study of the granulometric, mineral and chemical composition of the ore was carried out. A technological sample was presented for research, which is the result of averaging 12 samples taken at various points of the Buranny site of the Tomtor deposit.

The particle size distribution of the sample material was determined using a set of EKROS sieves (TU 3618-001-39436682-98).

The mineral composition of the ore sample examined was determined by the Leica MZ 125 stereoscopic microscope, the MBS-10 binocular microscope and the POLAM L-113 polarizing microscope. The error of the determinations corresponds to the standards for determining the mineral composition according to the IV category of accuracy (routine analysis) in accordance with OST 41-08-266-04.

The study of the material composition of the sample was carried out using the following methods:
- Mass spectral with inductively coupled plasma. Equipment: inductively coupled plasma mass spectrometer ELAN-6100.
- Atomic emission with inductively coupled plasma. Equipment: inductively coupled plasma atomic emission spectrometer Optima-4300.
- X-ray spectral. Equipment: X-ray spectrometer MagIX-Pro.
- Photometric. Equipment: photometer Lambda-35.

3. Results and discussion
The technological sample of the Tomtor ore deposit is a fine bulk material of dark olive color with a size of -2 to +0 mm. The ore moisture content is about 15%. The particle size distribution and content of the target components by size classes are shown in table 1.
Table 1. Particle size distribution and content of the main ore components

| Fraction size, mm | Fraction, % | Density specific (g/cm²) | Density bulk (g/cm³) | Content, wt % |
|-------------------|-------------|--------------------------|----------------------|---------------|
| -1+0 (original sample) | 100 | 3.42 | 1.55 | 19.8 | 4.00 | 22.5 | 0.062 |
| -1.0+0.5 | 5.8 | 3.43 | 1.57 | 19.5 | 3.15 | 21.8 | 0.052 |
| -0.5+0.315 | 14.8 | 3.54 | 1.58 | 20.4 | 3.37 | 19.0 | 0.060 |
| -0.315+0.1 | 47.4 | 3.56 | 1.58 | 20.1 | 3.57 | 18.2 | 0.064 |
| -0.1+0.045 | 6.8 | 3.55 | 1.62 | 21.6 | 4.00 | 20.8 | 0.078 |
| -0.045+0.020 | 5.0 | 3.56 | 1.65 | 22.8 | 4.44 | 22.6 | 0.090 |
| -0.020+0 | 20.2 | - | - | 22.5 | 4.65 | 22.1 | 0.092 |

According to the presented data, the particle size distribution of the ore in the sample is characterized by a fairly high content of fine particles. In this case, the mass fraction of particles with a size less than 100 µm is about 80%, less than 45 µm – about 25% and less than 20 µm – about 20%. Class ratios of various sizes, as well as the density values, are typical for pyrochlore-monazite-crandallite ores that have been pre-crushed according to the class -1+0 mm. The mineral and chemical composition of the test sample is shown in tables 2 and 3.

Table 2. Mineral composition of ore

| Mineral name | Content, % |
|--------------|------------|
| Gorceixite BaAl₃(PO₄)(PO₃OH) | 25 |
| Goyazite SrAl₃(OH)₄(HPO₄)₂(PO₄) | 20 |
| Florencite (Ce,La,Nd)Al₃(PO₄)₂(OH)₆ | 8 |
| Pyrochlore (Na,Ca)₂Nb₂O₆(OH,F) | 7 |
| Boehmite AlOOH | 4 |
| Apatite Ca₅(PO₄)₃(F,Cl,OH) | 3 |
| Monazite (Ce,La,Nd,Ca)(PO₄) | 13 |
| Quartz SiO₂ | 1 |
| Other (siderite, kaolinite, rutile) | 19 |

Table 3. Chemical composition of ore

| No. | Element (oxide) | Content, % | No. | Element (oxide) | Content, % |
|-----|----------------|------------|-----|----------------|------------|
| 1   | Ag            | <0.01      | 33  | Nb₂O₅          | 4.0        |
| 2   | Al₂O₃         | 14.4       | 34  | Nd₂O₃          | 2.5        |
| 3   | As            | 0.37       | 35  | Ni             | 0.007      |
The ore of the Tomtor deposit is a finely dispersed material, the particles of which are represented by polymineral aggregates of microcrystals in the size of a fraction of a micrometer, formed mainly by polymorphic modifications of phosphates with the general formula $(Sr, Ba, Ca)_x Al_3 (PO_4)_y (OH)_z$, in the crystal lattice of which Sr, Ba, and Ca atoms are partially replaced by rare-earth elements. In the initial and crushed ore samples, there are practically no separate (disclosed) particles of individual minerals.

| No. | Element (oxide) | Content, % | No. | Element (oxide) | Content, % |
|-----|----------------|------------|-----|----------------|------------|
| 4   | Au             | <0.003     | 36  | P_2O_3         | 22.5       |
| 5   | B              | 0.19       | 37  | Pb             | 0.25       |
| 6   | BaO            | 2.9        | 38  | Pd             | <0.005     |
| 7   | Be             | <0.001     | 39  | Pr_6O_11       | 0.62       |
| 8   | CaO            | 8.5        | 40  | Pt             | <0.005     |
| 9   | Cd             | 0.004      | 41  | Re             | <0.005     |
| 10  | CeO_2          | 9.3        | 42  | Rh             | <0.003     |
| 11  | Co             | <0.001     | 43  | Ru             | <0.0001    |
| 12  | Cr             | 0.06       | 44  | S              | 2.3        |
| 13  | CuO            | 0.14       | 45  | Sb             | <0.02      |
| 14  | Dy_2O_3        | 0.19       | 46  | Sc(Sc_2O_3)    | 0.04(0.061) |
| 15  | Er_2O_3        | 0.17       | 47  | SrO            | 3.7        |
| 16  | EuO            | 0.12       | 48  | SiO_2          | 1.9        |
| 17  | Fe             | 3.6        | 49  | Sm_2O_3        | 0.39       |
| 18  | Ga             | <0.05      | 50  | Sn             | <0.01      |
| 19  | Gd_2O_3        | 0.32       | 51  | Ta_2O_5        | 0.08       |
| 20  | Hf             | <0.002     | 52  | Tb_2O_7        | 0.03       |
| 21  | Hg             | <0.007     | 53  | Te             | <0.01      |
| 22  | Ho_2O_3        | 0.04       | 54  | ThO_2          | 0.14       |
| 23  | J              | <0.03      | 55  | TiO_2          | 6.7        |
| 24  | Jn             | <0.02      | 56  | Tm_2O_3        | 0.01       |
| 25  | Jr             | <0.01      | 57  | U              | 0.005      |
| 26  | La_2O_3        | 4.8        | 58  | V_2O_5         | 2.1        |
| 27  | Li             | 0.0005     | 59  | W              | <0.02      |
| 28  | Lu_2O_3        | 0.003      | 60  | Y_2O_3         | 1.16       |
| 29  | MgO            | 0.62       | 61  | Yb_2O_3        | 0.096      |
| 30  | MnO_2          | 0.9        | 62  | ZnO            | 0.42       |
| 31  | Mo             | <0.007     | 63  | ZrO_2          | 0.11       |
| 32  | Na             | 0.58       | 64  | ΣP_3O          | 19.75      |
of valuable elements. The ore sample is characterized by the uniformity with high heterogeneity of the mineral composition of the physical and mechanical properties of the ore material. The results presented in tables 2 and 3 allow us to make the following conclusions about the material composition of the ore of the Tomtor deposit. The ore in the sample is based on phosphates, carbonates and niobates. The main identified minerals are the minerals of crandallite group (gorceixite, goyazite and florencite), pyrochlore and monazite, in addition, clearly identified boehmite, apatite, and quartz. A group of other minerals includes siderite, kaolinite, rutile and some other minerals. It is established that the investigated ore belongs to a mineral variety of the pyrochlore-monazite-crandallite ores of phosphate-rare-metal type with a predominance of crandallite minerals (50%) and relatively low content of pyrochlore (~7%) in its composition. According to the content of niobium oxide Nb$_2$O$_5$ (~4%) in a sample, the ore can be attributed to the second class according to the accepted classification, i.e. the rich niobium ores, containing from 3.5 to 9% Nb$_2$O$_5$.

4. Conclusions
The ore is not abnormal in the content of industrial-valuable and rock-forming elements. This ore belongs to the pyrochlor-monazite-crandallite variety of phosphate-rare-metal ores with a relatively low content of niobium minerals and is rich in rare-earth element minerals. Considering the high complexity of the ore under study and the fine dispersion of mineral formations, we can conclude that it is practically impossible to enrich the ore of the Tomtor deposit using traditional methods. This conclusion is compatible with the results of studies [13-17]. However, considering the significant content of oxides of rare earth elements (~20%) and the relatively high content of niobium (~4% Nb$_2$O$_5$), the ore processing by combined pyro- and hydrometallurgy methods is considered promising and economically justified.

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