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New method of processing Ti-V ores resulting in reduced energy and increased technological effectiveness

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Abstract: Titanium and vanadium are among the elements with significant industrial importance, and demand for them has increased over the last few periods. The technology of titanium and vanadium ore processing is complex, especially for low-grade ores, where a dedicated process route should be applied. The paper presents potential benefits of increasing the technological and economic results of titanium and vanadium processing. Investigations are focused on the selected mining technologies, as well as comminution and separation operations.

Keywords: mineral processing, comminution, vanadium, titanium

1. Introduction

Titanium and vanadium are elements of significant economic importance, with applications including medicine, aerospace, the automotive industry, and the production of high-strength alloy steels. In particular, vanadium is a metal resistant to corrosion, and it can be utilized in the production of tubes and pipes for chemical transportation. Vanadium- and titanium-based alloys offer favorable strength-to-weight ratios, which makes it possible to utilize them in various engineering applications. A thick layer of vanadium can also be used to bond titanium to steel, which is particularly valuable in aerospace engineering. When titanium is combined with vanadium and iron, it enables the development of wind turbines that operate at very high rotational speeds. Vanadium is equally important in nuclear energy applications, and in its oxide form, it is used in the production of superconducting magnets. Both titanium and vanadium play a crucial role in renewable energy technologies. Titanium is a key material in wind turbines, while vanadium is used in all-vanadium redox flow batteries, which store electricity generated from renewable sources such as wind and solar power. These metals also contribute to greater energy efficiency. Titanium is widely used in heat exchangers, helping to increase the efficiency of power plants and industrial systems. Vanadium, on the other hand, strengthens steel, allowing the production of lighter, more fuel-efficient vehicles. In addition, titanium and vanadium support environmental protection efforts. The first can be used in water treatment processes to remove contaminants, while the latter is applied in catalytic converters to help reduce emissions from petrol and diesel engines.

Vanadium occurs, among others, in titanomagnetite deposits, which are currently its main source, whereas titanium is always found in ores of other elements. Vanadium–titanium magnetite is a significant type of Ti-V ore. It is commonly found in magmatic deposits and is processed for its vanadium, titanium, and iron contents (Gao et al., 2022; Jena et al., 1995). The other ore minerals include magnetite, ilmenite, and titanomagnetite, and all are oxides.

Titanium is extracted from primary magmatic deposits and secondary placer deposits, with ilmenite as the dominant mineral in both types. Vanadium in magmatic ores occurs as an admixture in magnetite, Ti–magnetite, and ilmenite.

The global reserves of high-grade TiO_2 of ilmenite and rutile are about 62 Mt and 880 Mt, respectively, while the global reserves of vanadium–titanium magnetite are 58 Gt (Woodruff et al., 2017) which is far more than the reserves of other titania-containing minerals.

The annual mining production of vanadium amounts to 100,000 t, with the main producers being China (63,800 t), Russia (20,100 t), the USA (8,800 t), and Brazil (7,200 t). Titanium production in the form of TiO_2 is approximately 8.5 Mt, 97% of which comes from ilmenite (leucoxene) ores, while rutile production amounts to 0.6 Mt. The main producers are China (33.6%), Mozambique (13.3%), South Africa (10.6%), Australia (7.3%), and Ukraine (5.8%). According to World Mining Data, the mining production concerns 23 countries, but the ones listed above account for 70.6% of global production. Over the past five years, the production of each of these elements has increased by approximately 20%.

The extraction of titanium–magnetite ores requires the application of complex technological processing methods due to the complicated mineralization of these ores, their low grade, and the dispersion of the valuable component. These processes mainly involve size reduction and separation, with the primary challenge being to improve the process performance from a technological standpoint while reducing energy consumption.

The processing of vanadium–titanium magnetite ores often involves managing complex mineral associations and the need for advanced separation techniques to recover the valuable metals efficiently (Goncharov et al., 2025; Zhu et al., 2023). The beneficiation process utilizes techniques suitable for oxide ores, such as magnetic separation and magnetization roasting (Han et al., 2021; Xu et al., 2017). These methods are effective due to the magnetic properties of the oxide minerals.

Size reduction operations of crushing and grinding are the most energy- and capital-intensive unit operations in mineral processing and typically account for 30–70% of the overall energy used by mining operations, while industrial comminution operations consume around 3% of total electric energy (Baawuah et al., 2025; Tromans, 2008). The energy consumption used for grinding is very high compared with the preceding size reduction stages, blasting and crushing. For example, the distribution of energy at a copper mine site is 3–5% for blasting, 5–7% for crushing, and 80–90% for grinding (Jeswiet & Szekeres, 2016).

However, the problem appears with low-grade, complex, V-bearing titanomagnetite deposits, specifically with economically and technologically efficient processing technologies. These deposits are very difficult to beneficiate with state-of-the-art extraction and mineral processing technologies due to the complex spiderweb-like mineral assemblages in which the ilmenite mineral occurs as both large external granules and sandwich exsolutions appearing within the V-bearing magnetite particles. Without novel selective blasting and advanced mineral (and metal) extraction methods, it is almost impossible to cost-effectively co-produce Ti, V, and Fe from these ores. The presented paper highlights potential options for processing Ti-V ores through the application of specific technological circuits.

2. Investigative program

The innovative approach to the technology of Ti-V ore processing seems to be one of the crucial aspects enhancing its effectiveness. The paper presents selected issues aiming at optimizing this process, especially through the application of various crushing technologies, which is only a part of broader investigations. The overarching aim can be defined as optimizing the production of the metals through increasing the liberation of useful minerals by selective blasting, followed by selective fragmentation technologies and efficient downstream separation methods (Fig. 1). The main objective in the size-reduction stage is to limit the unfavorable phenomenon of material overgrinding and the generation of very fine particles of crushing and grinding products, all while decreasing the energy consumption. The concept of the investigations includes the value chain starting from the deposit and finishing at the concentrates of Ti-V that constitute the feed material for metallurgical processes.

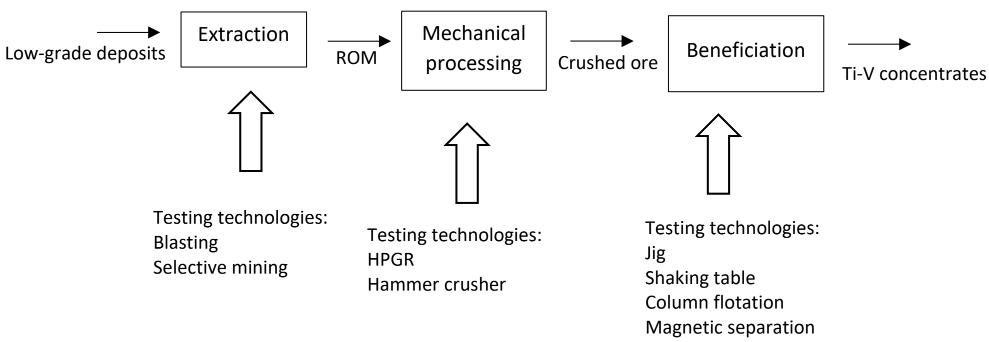

Fig. 1. Idea of investigations

The extraction process of ROM (run-of-mine) from low-grade deposits includes selective blasting, and investigations in this context include the selection of blasting parameters through a testing program. The main result of these investigations should contribute to increasing the liberation of useful minerals from the gangue. This method of extraction potentially influences the stage of rock breakage by reducing the consumption of crushing energy. It can also indirectly contribute to the separation of ilmenite and magnetite.

The processing stage includes two steps: size reduction of the ROM material and separation of operations. The size reduction stage is based on high-pressure comminution in a high-pressure grinding rolls (HPGR) device. The hammer crusher is treated as a reference device for comparing the effects of energy savings and breakage intensity. Separation tests were carried out for the jig and concentrating table in the first part, then for magnetic separation in high- and low-intensity magnetic fields.

The material characterization has been focused on the ROM material and obtained streams of concentrates and tails, and included the following analyses:

- laser-diffraction particle size analyses, especially for the ROM and concentrates;
- 2D and 3D textural mapping and meso-scale elemental distributions for extracted ore samples;
- qualitative mineralogy in X-ray diffraction (XRD), field emission gun scanning electron microscope (FEG-SEM), and Raman spectroscopy;
- quantitative mineralogy, including mineral particle size distribution (PSD), associations, and liberations using automated mineralogy by means of quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN) and mineral liberation analysis (MLA);
- mineral chemistries for understanding the metal deportment;
- measurements of total metals and the general mass balance equation.

At the stage of comminution, the two main technologies under testing are the HPGR device and the hammer crusher (HC). The HPGR crushes the material primarily by means of interparticle compression and has lower energy consumption than the hammer crusher. On the other hand, the hammer crusher usually operates at greater comminution ratios, which is connected with the specifics of impact breakage. This results from their operating principles; crushing in HPGR devices is based on slow compression with free crushing (Paasovaara et al., 2024) while the hammer crusher utilizes the kinetic energy of the material to disintegrate particles via particle–particle and particle–crusher plate collisions. The HPGR and HC can operate without water. The testing scheme is presented in Fig. 2.

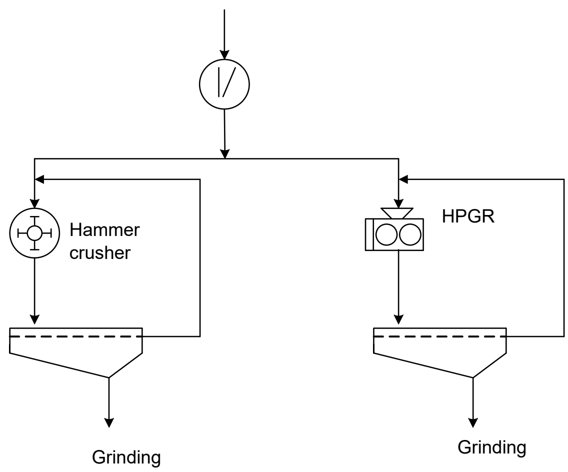

Fig. 2. Comminution circuit under testing

The beneficiation testing includes two directions: separate investigations on coarser crushed ore and finer particle size fractions. Coarser material (screening oversize product) was tested via jig beneficiation according to Fig. 3.

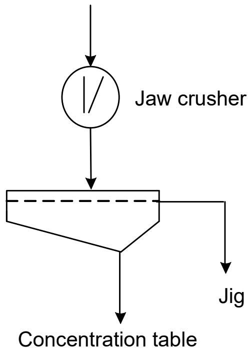

Fig. 3. Scheme of gravitational separation route under testing

The main idea of testing this configuration was to investigate the potential for preconcentration of titanium and vanadium-bearing minerals in the relatively simpler and less cost-consuming processes of magnetic separation and flotation. Additionally, preconcentration by means of gravitational methods does not always involve deep grinding, which opens up the potential for reducing energy costs.

The next step of the investigative program includes tests on magnetic separation and flotation, which are considered the primary beneficiation technologies that are capable of efficiently handling low-grade complex Ti-V bearing ores. Investigations on magnetic separation involve a combination of operations carried out in a low-intensity magnetic field (LIMS – low-intensity magnetic separator) and in a high-intensity magnetic field (HIMS). In the first stage of testing, only dry magnetic separation was tested. The initial configuration of the circuit under testing is presented in Fig. 4.

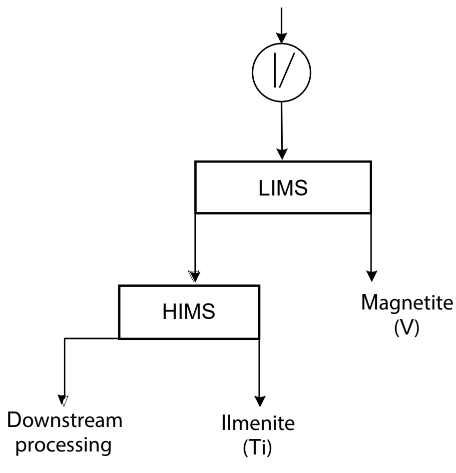

Fig. 4. Scheme of magnetic separation tests

Various configurations of this circuit (Fig. 4) are considered, i.e. regrinding of semi-product, different grinding intensities (different particle size distributions of the feed), together with different layouts of flotation operations. The key purposes of applying the flotation process are to clean the final concentrate, to increase the Ti and V grade, and to investigate the selectivity and collectivity of the separation of ilmenite (Ti-bearing mineral) and magnetite (V-bearing mineral).

As was underlined in the previous section, the main result concerns the optimization of titanium and vanadium ore extraction and processing. Individual components of this target include:

- blasting model determined based on characteristics of the blasting products and process parameters. The material characteristics mainly concern intergranular cracks;
- adjustment of comminution technology through comparative tests of technologies with potentials for selective fragmentation with conventional crushing techniques (HPGR and HC);
- validation of preconcentration methods based on gravity separation (jig separation and shaking table) for coarser particles of crushing products;
- magnetic separation in low- and high-intensity fields;
- flotation process, especially the comparison of column flotation with conventional cell flotation;
- waste handling.

3. Results

The main outcome of the investigations is to determine an innovative method enabling the production of ilmenite-rich titanium preconcentrates and ilmenite-free vanadium products. The approach assumes the use of the latest technologies, which are intended to significantly reduce the energy and water consumption during ore extraction and processing. The final technology developed can be applied to currently unexploited deposits of V-bearing titanomagnetite occurring in various countries. These deposits often contain significant amounts of vanadium, but their recovery by means of currently applied technologies is economically ineffective due to their complex mineral composition and types of mineralization.

Main results relating to the comminution stage:

- achieving a higher comminution ratio through the application of an energy- and technologically efficient technology of high-pressure grinding using HPGR presses,
- reducing the specific energy consumption in the comminution process of titanium–vanadium ores.

Figure 5 presents the results of laboratory-scale crushing tests, in the form of particle size distribution curves for HC and HPGR products. It can be seen that the HPGR product appeared more intensely crushed in the range of sizes below 0.8 mm, which means that the press device is capable of producing a higher yield of the finest particle size fractions, potentially contributing to more intense liberation. To some extent, this was confirmed through the obtained values of Bond work indices: Wi = 14.5 kWh/Mg for the HC, and Wi = 14.1 kWh/Mg for the HPGR.

The obtained results were reflected in the outcomes achieved in the mill (Tab. 1). After 10 min of grinding, the value of crushing ratio S for the coarsest particles in the HPGR press was higher than for the HC product. It should also be mentioned that the variations between results achieved for the HPGR and HC products are not huge, but this is due to the scale of the experiments. In plant operations, the results may be more favorable for HPGR devices.

In the next stage, an investigation into separation technologies will be carried out, with expected outcomes including: increasing the technological efficiency of beneficiation processes by improving the recovery of valuable components in concentrates, and enhancing the economic efficiency of the process through the reduction of processing costs. A holistic approach to the problem also takes into account social and environmental benefits, which complement the energy and technological gains. These benefits include the potential to substantially reduce the greenhouse gas (GHG) emissions intensity per ton of material (metal, metal content, concentrate, or mineral) sold into the downstream value chain. Specifically, this aims to increase the value of low-grade deposits through the development of processing knowledge of global relevance, while improving the traceability of raw materials. It may also present an opportunity to increase the sourcing of vanadium–titanium raw materials from European deposits and processing plants, and to improve the responsible supply of raw materials to Europe.

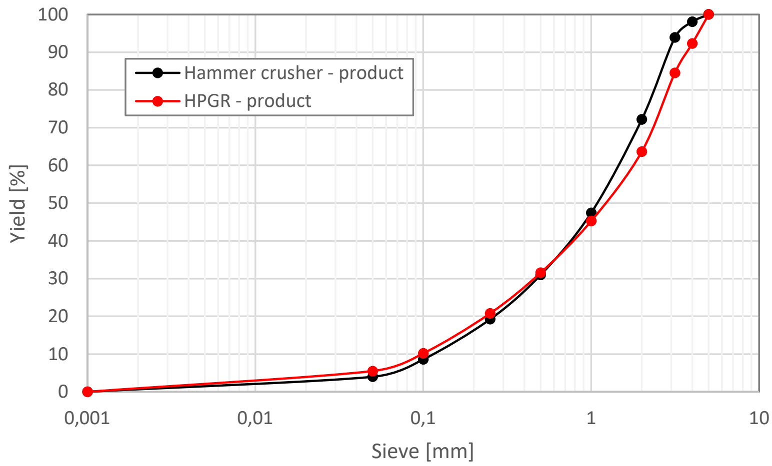

Fig. 5. Particle size distribution curves for HPGR and HC products

Tab. 1. Comminution ratios for HPGR and HV products achieved in a grinding stage in a laboratory ball mill

Grinding duration	Grinding time [min]	HC	HPGR
S90	5	6.0	1.6
S10	5	5.0	3.7
S90	10	13.0	14.8
S10	10	6.0	5.0

4. Conclusions

Based on the presented investigative program, it is possible to achieve the following targets:

1. Determine an efficient method of comminution contributing to the effective liberation of Ti and V-bearing minerals, i.e., ilmenite and magnetite. It is expected to increase the liberation for 20%, compared to conventional comminution methods.
2. Work out a dry separation method for Ti and V preconcentrates at recoveries 70%, with specific grades (45% of ilmenite and 1% of vanadium oxide), accepted in downstream pyro- and hydrometallurgical treatment.
3. Work out a wet separation circuit with low water consumption for efficient separation of useful minerals from the gangue. The assumed values of recovery and concentrate grades are similar to the levels presented in conclusion 2.

The projected technology also assumes zero waste or a low level of waste generation; therefore, it is necessary to evaluate the potential utilization of process waters after purification. For this purpose, it is necessary to identify the ionic compounds that accumulate in recycled process waters, to investigate their impact on the course of the preliminary concentration process, and to determine the most efficient water treatment procedures that will enable the most effective pre-concentration process in combination with water recycling.

The research program is therefore structured as a multi-stage investigation encompassing selected comminution technologies as well as gravity, magnetic, and flotation-based beneficiation methods. The findings in this area will be presented in subsequent publications.

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