MINERAL PROCESSING OF NON-FERROUS METALS / ОБОГАЩЕНИЕ РУД ЦВЕТНЫХ МЕТАЛЛОВ

UDC 622.7′1
https://doi.org/10.17073/0021-3438-2023-6-5-12

Research article
Научная статья

Application of microwave radiation for decrepitation of spodumene from the Kolmozerskoe deposit

O.N. Krivolapova[1], **I.L. Fureev**[2]

[1] **National University of Science and Technology "MISIS"**
4 build. 1 Leninskiy Prosp., Moscow 119049, Russia

[2] **State Research and Design Institute of the Rare Metal Industry (Giredmet JSC)**
2 build. 1 Elektrodnaya Str., Moscow 111524, Russia

✉ Ilya L. Fureev (ifureev@mail.ru)

Abstract: The lithium-ion industry is experiencing a rapidly growing demand for compounds containing lithium. Spodumene is one of the primary industrial minerals used in the production of this metal. It exists in three polymorphic forms. In its natural state, it is known as α-spodumene, which possesses a high resistance to chemical attack due to its compact structure containing silicon and aluminum oxides. When subjected to microwave radiation, α-spodumene undergoes a transformation, first becoming the γ form and then transitioning to the β form. It is known that the β form can be chemically treated to extract lithium. In light of this, microwave exposure was applied to α-spodumene with the aim of decrepitation, followed by sulfuric acid decomposition of the mineral. The mineral was crushed into different sizes (1.0, 0.5, and 0.25 mm). Temperature changes, induced by both conventional and microwave heating, were analyzed. The heating process was continued for samples of various sizes until a temperature of 1200 °C was reached. Sulfation of calcined samples was carried out for 60 minutes at a temperature of 250 °C. After cooling to 22 °C, distilled water was added and mixed for 120 minutes in closed leaching vessels. To determine the recovery of valuable and associated components, leach cakes and the liquid phase were analyzed using inductively coupled plasma atomic emission spectrometry. Based on the analysis of experimental results, the feasibility of using microwave radiation for decrepitation of spodumene to extract lithium is confirmed. The influence of particle size on phase transformations and, consequently, the degree of lithium extraction from spodumene was investigated. It was found that the recovery of lithium during the microwave action and leaching process for particles smaller than 0.25 mm reached 96.82 %. Microwave heating resulted in lower recovery rates of "harmful" components, such as iron, sodium, and calcium, in the leaching process, leading to a higher purity of the resulting product.

Keywords: lithium, spodumene, microwave radiation, decrepitation, sulfation, leaching.

For citation: Krivolapova O.N., Fureev I.L. Application of microwave radiation for decrepitation of spodumene from the Kolmozerskoe deposit. *Izvestiya. Non-Ferrous Metallurgy*. 2023;29(6):5–12. https://doi.org/10.17073/0021-3438-2023-6-5-12

Применение микроволнового излучения для декрипитации сподумена Колмозерского месторождения

О.Н. Криволапова[1], **И.Л. Фуреев**[2]

[1] **Национальный исследовательский технологический университет «МИСИС»**
119049, Россия, г. Москва, Ленинский пр-т, 4, стр. 1

[2] **Государственный научно-исследовательский и проектный институт редкометаллической промышленности (АО «Гиредмет»)**
111524, Россия, г. Москва, ул. Электродная, 2, стр. 1

✉ Илья Леонидович Фуреев (ifureev@mail.ru)

Аннотация: Литий-ионная промышленность демонстрирует быстрорастущий спрос на Li-содержащие соединения. Сподумен является одним из основных промышленных минералов для производства этого металла. Он имеет 3 полиморфные формы.

В природе – это α-сподумен, который обладает высокой устойчивостью к химическому воздействию благодаря своей компактной структуре, содержащей оксиды кремния и алюминия. Микроволновое излучение превращает α-сподумен сначала в γ-, а после в β-форму, и известно, что последняя может подвергаться химическому воздействию с целью извлечения лития. Основываясь на этом факте, была проведена микроволновая процедура воздействия на α-сподумен, направленная на декрипитацию с последующим серно-кислотным разложением минерала, измельченного до разной крупности (1,0, 0,5 и 0,25 мм). Также были проанализированы зависимости изменения температуры при использовании традиционного нагрева. Обычный и микроволновый нагревы образцов различной крупности проводили до достижения температуры 1200 °С. Сульфатизацию прокаленных образцов осуществляли в течение 60 мин при t = 250 °С. После охлаждения до 22 °С добавляли дистиллированную воду и перемешивали в течение 120 мин в закрытых сосудах для выщелачивания. Для определения извлечения ценных и попутных компонентов был проведен анализ кеков выщелачивания и жидкой фазы методом атомно-эмиссионной спектрометрии с индуктивно связанной плазмой. На основе анализа результатов экспериментов обоснована рациональность применения микроволнового излучения для декрипитации сподумена с целью извлечения лития. Изучено влияние крупности на фазовые превращения и, соответственно, степень извлечения лития из сподумена. Показано, что извлечение лития в процессе микроволнового воздействия и выщелачивания класса менее 0,25 мм достигло 96,82 %. Микроволновый нагрев привел к более низким показателям извлечения «вредных» компонентов, таких как железо, натрий и кальций, в процессе выщелачивания, что дает преимущество в чистоте получаемого продукта.

Ключевые слова: литий, сподумен, микроволновое излучение, декрипитация, сульфатизация, выщелачивание.

Для цитирования: Криволапова О.Н., Фуреев И.Л. Применение микроволнового излучения для декрипитации сподумена Колмозерского месторождения. *Известия вузов. Цветная металлургия*. 2023;29(6):5–12.
https://doi.org/10.17073/0021-3438-2023-6-5-12

Introduction

Lithium, a metal with unique physical and chemical properties such as a high specific heat capacity, good conductivity, and strong chemical activity, is finding increasing applications across various industries and technologies. Its utility has expanded from traditional sectors like metallurgy, energy, aerospace, and medicine to the forefront of green energy technologies [1—3]. The current surge in the lithium market is predominantly fueled by the growing demand for energy storage devices [4]. In order to meet the projected lithium demand by 2030, there are plans to achieve the designed capacity of the Russian joint venture between MMC Norilsk Nickel and Rosatom for processing rare metal pegmatites from the Kolmozerskoe deposit (Murmansk Oblast, Russia) [5].

Sulfuric acid leaching is one of the methods employed to extract lithium carbonate from spodumene concentrates. Kola MMC is set to become the largest sulfuric acid producer in the Murmansk Oblast by 2027. They have plans to initiate copper production using the roasting—leaching—electroextraction process [6]. As a byproduct of this process, sulfuric acid will be generated, making it practical to utilize in the processing spodumene from the Kolmozerskoe deposit.

Currently, lithium production in the industry relies on three primary sources [7—9]:

— solid mineral resources, including spodumene, complex Li—Be-pegmatite ores — 50 %, and lithium mica — 20 %;

— liquid mineral resources, encompassing brines, and lake brines, oil formation waters, and thermal waters — 20 %);

— secondary raw materials, which consist of batteries, accumulators, and chemical current sources — 10 %).

Among these industrial minerals used for lithium extraction, spodumene holds significant importance [10]. Its chemical composition includes lithium oxide (8.1 %), aluminum oxide (27.4 %), and silicon dioxide (64.5 %) [11]. The pegmatites from the Kolmozerskoe deposit are not only a valuable source of lithium but also beryllium, tantalum, niobium, and other metals [12].

Spodumene can exist in three distinct modifications: α, β, γ [1]. Natural spodumene is naturally found in the crystalline α phase. The β form results from recrystallization when α spodumene is heated at temperatures within the range of 900 to 1100 °C [13; 14], with complete transformation occurring up to 1100 °C. The γ modification of spodumene is a metastable phase that occurs when α spodumene is heated to temperatures ranging from 700 to 900 °C [2; 15]. The γ phase is characterized by low reactivity and a limited degree of lithium extraction, underscoring the need for decrepitation [16; 17].

Traditional methods of thermal decrepitation have several disadvantages, including high energy consumption and adverse environmental impacts [18]. Additionally, the transportation of hydrocarbon energy resources to the production region in the Murmansk Oblast leads to added costs in the production of finished products. Therefore, it is crucial to assess the feasibility of using microwave radiation in comparison with conventional decrepitation methods.

When compared to conventional heating, microwave heating offers several advantages, including resource savings, shorter processing times, more controlled heating processes, and direct, non-contact selective and bulk heating [11]. Achieving uniform heating throughout the entire material bulk can increase the porosity of the carrier mineral, thereby reducing the required sintering time and the temperature of chemical reactions, while also enhancing the diffusion of the leaching agent within the mineral and improving recovery rates [12; 19]. Consequently, the use of ultrahigh-frequency (microwave) heating for the decrepitation of spodumene can be an efficient and cost-effective method. However, further research is necessary to assess its feasibility.

In terms of their interaction with microwaves, materials can be categorized into three groups: transparent, conductive/opaque, and absorbing [6]. Low dielectric loss materials, such as spodumene, are challenging to heat. However, they can absorb microwaves at elevated temperatures due to increased dielectric losses. Therefore, for microwave heating of such materials, a combined method is typically employed [20]. In this approach, materials are preheated by another heat source to a specific temperature at which they become more efficient in absorbing microwave radiation before being exposed to microwaves directly [13].

The mechanism and the impact of hybrid microwave on the structural changes of spodumene have not been comprehensively studied. Discrepancies in the results of phase transformations observed in spodumene polymorphs at high temperatures can be attributed to differences in grain sizes, impurity concentrations, amorphous materials formed during grinding, as well as variations in experimental setups, heating methods, and temperature measurements [21; 22]. However, the influence of process parameters on the phase transformations of spodumene from the Kolmozerskoe deposit and its leachability has not been thoroughly investigated.

In order to explore the potential advantages of both microwave and direct decrepitation methods, this study examines the calcination of spodumene using microwave radiation, investigates the impact of microwave and direct methods at different material sizes on phase transformations, and consequently assesses the leachability of this mineral. Furthermore, it compares microwave heating with standard methods.

Materials and methods

Mineralogical studies have revealed that the ore from the Kolmozerskoe deposit comprises approximately 20 % spodumene (~1.5÷1.6 % Li_2O), about 30 % quartz, 30 % albite, 15 % microcline, 5 % muscovite, along with traces of zircon and tourmaline [23].

Traditionally, spodumene ores are enriched to yield a concentrate containing roughly 5.0—6.0 % Li_2O and less than 1 % Fe_2O_3 as the raw material for subsequent calcination processes and lithium extraction [24]. For the experiments, spodumene was manually sampled from the ore mass and subjected to analysis. The sample was initially crushed to a particle size of –1 mm, after which quartered samples were further crushed to ensure 100 % content of classes smaller than 0.5 and 0.25 mm. The chemical composition of the quartered samples for research was as follows, wt.%:

Li_2O	5.6
Al_2O_3	25.1
SiO_2	65.7
Fe_2O_3	0.7
Na_2O	1.0

To investigate the efficiency of microwave calcination of the spodumene concentrate and the impact of feedstock size, experiments were conducted to calcine size classes less than 1.0, 0.5, and 0.25 mm. The temperature profiles of the samples over time during direct heating are depicted in Fig. 1.

Samples with particle sizes less than 1.0, 0.5, and 0.25 mm were exposed to direct heating in a muffle furnace, reaching a temperature of 1200 °C. During the initial 10 min of the process, they exhibited varying heating rates, but after this time, the rates equalized and stabilized at approximately 30 °C/min.

The microwave heating of the spodumene concentrate was conducted in a specialized microwave chamber equipped with independent magnetrons and a control system, enabling the adjustment of a 1 kW microwave power at a frequency of 2.5 GHz, along with temperature monitoring. In each test, a 100 g sample of spodumene concentrate was placed in glassware, chosen for its transparency to microwave radiation. The thickness of the material layer remained consistent at 10 mm. Temperature profiles illustrating the relationship between

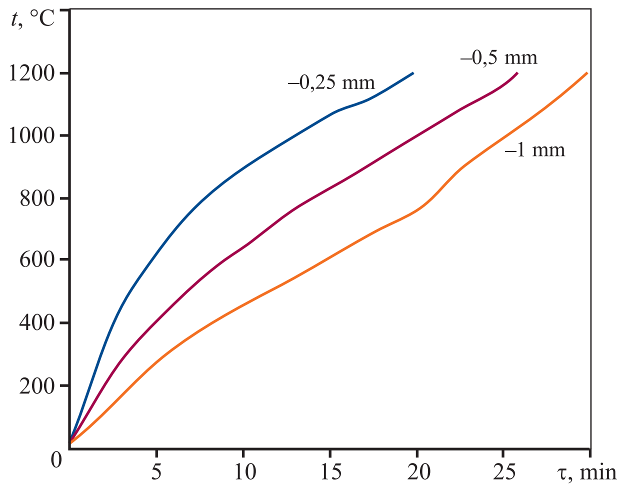

Fig. 1. Temperature as a function of heating duration in a muffle furnace

Рис. 1. Зависимость температуры образцов разной крупности от продолжительности нагрева в муфельной печи

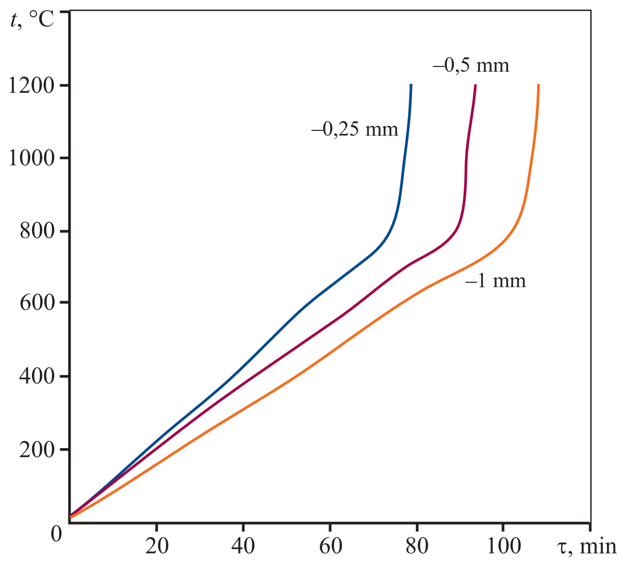

Fig. 2. Temperature as a function of microwave heating duration

Рис. 2. Зависимость температуры образцов разной крупности от продолжительности микроволнового нагрева

temperature and microwave exposure time are presented in Fig. 2.

The efficiency of microwave heating is contingent on the thermophysical properties of the sample [25]. Spodumene exhibits weak absorption of microwave radiation at low temperatures. The heating rate follows a linear pattern up to approximately 700 °C, at which point it reaches around 20 °C/min. This rate is lower compared to direct heating in a muffle furnace. Beyond 800 °C, there is a sharp increase in the heating rate, reaching about 70 °C/min. This significant change is attributed to alterations in the dielectric properties of spodumene as it crosses the critical temperature of approximately 634 °C [13], which explains the rapid acceleration in its heating rate. As the temperature rises to around 800 °C, the heating profiles rapidly become nearly exponential, enabling the temperature to reach 1200 °C in approximately 6 min.

The results indicate that the time required to raise the temperature from 800 to 1200 °C is considerably shorter when microwave radiation is employed. The direct heating method yields the best results for $t < 800$ °C. The temperature profiles depicted in Figs. 1 and 2 highlight the efficiency of microwave hybrid heating of spodumene.

The temperature profiles for different heating methods reveal that smaller spodumene particles undergo a faster transformation into β spodumene with shorter heat exposure times. This implies that particle size has an impact on both microwave and direct heating of spodumene.

The leaching properties of samples subjected to microwave and conventional calcination methods were compared. To extract lithium from the calcined samples, specifically β-spodumene, a process involving sulfatizing roasting followed by water leaching was carried out. In this process, concentrated sulfuric acid was introduced to the calcined sample. The mixture was then heated in an oven at a temperature of 250 °C for 60 min. Following sulfatizing roasting and subsequent cooling to room temperature, distilled water was added, and the resulting mixture was stirred for 120 min at ambient temperature with agitation at 200 rpm. This step was performed to leach the soluble lithium sulfate that was produced during the roasting process. The filtrate, containing the dissolved components, was then separated from the solid residue using a Büchner funnel, Bunsen flask, and filter paper. The leaching cakes and the resulting solutions were analyzed for their Li, Fe, Na, and Ca content. It's important to note that only samples with a particle size smaller than 0.25 mm were investigated in this study.

Results and discussion

Table presents a summary of the metal balance following conventional and microwave radiation treatments.

For direct heating, the lithium extraction rate was 97.37 %, while the microwave procedure yielded a slightly lower rate of 96.82 %. These results indicate that α-spodumene exhibits very low reactivity, suggest-

Metal balance

Баланс металла

Product	Weight (volume), g (ml)	Content, % (g/l)				Extraction, %			
		Li	Fe	Na	Ca	Li	Fe	Na	Ca
Heating in a muffle furnace									
Product solution	(100.02)	(1.27)	(0.02)	(0.30)	(0.57)	97.37	9.81	72.25	94.32
Leaching cake	98.35	0.03	0.22	0.12	0.03	2.63	90.19	27.75	5.68
Initial material	100.00	1.30	0.24	0.42	0.60	100.00	100.00	100.00	100.00
Microwave heating									
Product solution	(100.04)	(1.26)	(0.01)	(0.16)	(0.23)	96.82	5.06	37.36	38.04
Leaching cake	98.23	0.04	0.23	0.27	0.38	3.18	94.94	62.64	61.96
Initial material	100.00	1.30	0.24	0.42	0.60	100.00	100.00	100.00	100.00

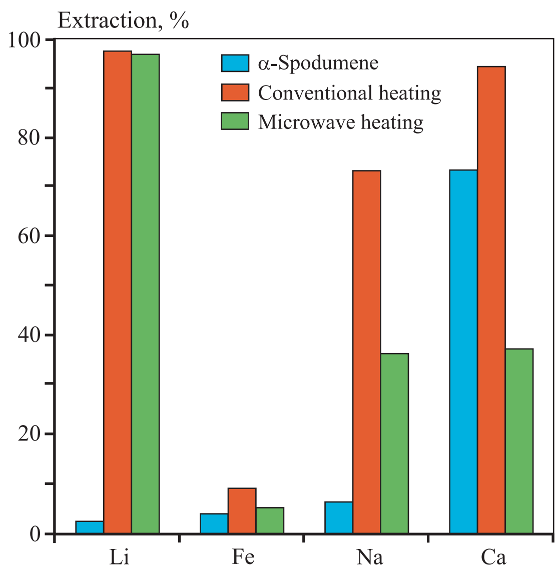

Fig. 3. Extraction of major elements by leaching from initial spodumene concentrates and calcined by microwave and conventional methods

Рис. 3. Извлечение основных элементов при выщелачивании из необработанного и прокаленного с помощью микроволнового и обычного методов нагрева образцов концентрата сподумена

ing limited efficiency in lithium leaching. Fig. 3 illustrates the recovery of iron, sodium, and calcium through leaching from initial spodumene concentrates and those subjected to calcination by both microwave and conventional methods. The obtained results indicate that the extraction of these elements was lower under microwave exposure, providing an advantage over conventional heating in subsequent stages of lithium extraction from the resulting solutions.

Conclusions

In this study, the impact of microwave radiation power on lithium leaching was thoroughly investigated. As the temperature increases to approximately 700 °C, the microwave heating rate experiences a sharp rise, allowing it to reach 1200 °C in approximately 6 minutes. The research has confirmed that microwave power plays a significant role in influencing phase transformations and, consequently, the leaching of calcined samples of spodumene concentrate.

The study has also revealed that the most efficient heating method involves a combination of conventional and microwave treatments on the sample. Based on the research findings, it is suggested that traditional heating should be applied up to a temperature of 800 °C, after which microwave exposure is initiated. This approach allows for achieving the maximum heating rate.

With the combined method, it becomes possible to reach a temperature of 1200 °C in approximately 14 minutes, which is significantly quicker compared to 20 and 80 min required for conventional and microwave exposure, respectively.

By using microwave radiation, a lithium recovery rate of 96.82 % was achieved, which is comparable to the recovery rate of the calcined sample under conventional heating. Moreover, microwave calcination resulted in lower impurity levels in the leachate, presenting an advantage in downstream processing stages.

An establishment of a pilot plant for implementing the combined heating procedure and conducting additional research will enable further validation and refinement of the results obtained.

References

1. Salakjani N.K., Singh P., Nikoloski A.N., Production of lithium — a literature review Pt. 1: Pretreatment of Spodumene. *Mineral Processing and Extractive Metallurgy Review*. 2020; 41(5):335—348. https://doi.org/10.1080/08827508.2019.1643343
2. U.S. Geological Survey Mineral commodity summaries 2023. Reston, 2023. 214 p. URL: https://www.kriittisetmateriaalit.fi/wp-content/uploads/2023/02/Mineral-Commodity-Summaries-2023-USGS-Jan-2023.pdf (accessed: 15.06.2023).
3. Kurkov A.V., Mamoshin M.Yu., Anufrieva S.I., Rogozhin A.A. Breakthrough technologies for the direct extraction of lithium from hydromineral raw materials In: *Mineral resource base of high-tech metals. Development, reproduction, use: Proceedings of the Second scientific and practical conference with international participation* (Moscow, December 07—08, 2021). Moscow: FGBU “VIMS”, 2021. P. 175—189. (In Russ.).
Курков А.В., Мамошин М.Ю., Ануфриева С.И., Рогожин А.А. Прорывные технологии прямого извлечения лития из гидроминерального сырья. В сб.: *Минерально-сырьевая база металлов высоких технологий. Освоение, воспроизводство, использование: Труды Второй научно-практической конференции с международным участием* (г. Москва, 07—08 декабря 2021 г.). М.: ФГБУ «ВИМС», 2021. С. 175—189.
4. Infomine Report «Overview of the market of spodumene and lithium hydroxide in the world». Moscow: Infomine, 2021. 179 p. URL: http://www.infomine.ru/research/38/650/ (accessed: 17.04.2023). (In Russ.).
Отчет «Обзор рынка сподумена и гидроксида лития в мире». М.: ООО «ИГ «Инфомайн», 2021.179 с. URL: http://www.infomine.ru/research/38/650/ (дата обращения: 17.04.2023).
5. Stepanov S.S. Joint venture of Norilsk Nickel and Rosatom received the right to develop the Kolmozerskoye deposit. URL: www.nornickel.ru/news-and-media/press-releases-and-news/sovmestnoe-predpriyatie-nornikelya-i-rosatoma-poluchilo-litsenziyu-na-razrabotku-kolmozerskogo-mestorozhdeniya/ (accessed: 15.06.2023). (In Russ.).
Степанов С.С. Совместное предприятие «Норникеля» и «Росатома» получило право на разработку Колмозерского месторождения. URL: https://www.nornickel.ru/news-and-media/press-releases-and-news/sovmestnoe-predpriyatie-nornikelya-i-rosatoma-poluchilo-litsenziyu-na-razrabotku-kolmozerskogo-mestorozhdeniya/ (дата обращения: 15.05.2023).
6. Kasikov A.G., Shchelokova E.A., Yakovlev K.A., Korovin V.N., Glukhovskaya I.V. Sulfuric acid decomposition of the spodumene concentrate of the Kolmozerskoe deposit. In: *Proceedings of the Kola Scientific Center of the Russian Academy of Sciences. Series: Engineering Sciences*. 2023;14(2):102—106. (In Russ.). http://dx.doi.org/10.37614/2949-1215.2023.14.2.018
Касиков А.Г., Щелокова Е.А., Яковлев К.А., Коровин В.Н., Глуховская И.В. Сернокислотное разложение сподуменового концентрата Колмозерского месторождения. *Труды Кольского научного центра РАН. Сер.: Технические науки*. 2023;14(2):102—106. http://dx.doi.org/10.37614/2949-1215.2023.14.2.018
7. Tadesse B., Makuei F., Albijanic B., Dyer L. The beneficiation of lithium minerals from hard rock ores: A review. *Minerals Engineering*. 2019;131:170—184. https://doi.org/10.1016/j.mineng.2018.11.023
8. Youqi Fan, Hu Li, Chang Lu, Shiliang Chen, Yonglin Yao, Hanbing He, Shuai Ma, Zhen Peng, Kangjun Shao. A novel method for recovering valuable metals from spent lithium-ion batteries inspired by the mineral characteristics of natural spodumene. *Journal of Cleaner Production*. 2023; 417(7):41—48. https://doi.org/10.1016/j.jclepro.2023.138043
9. Zhang S.J., Cui L.W., Kong L.H., Jiang A.L., Li J.B. Summarize on the lithium mineral resources and their distribution at home and abroad. *Nonferrous Metals Engineering*. 2020;10(10): 95—104. https://doi.org/10.3969/j.issn.2095-1744.2020.10.015
10. Zhang L., Yang H.P., Liu L., Ding G.F. 2020. Global technology trends of lithium extraction. *Conservation and Utilization of Mineral Resources*. 2020; 40(5): 24—31. https://doi.org/10.13779/j.cnki.issn1001-0076.2020.05.004
11. Roskill: CO_2 emissions from lithium production set to triple by 2025. URL: https://www.greencarcongress.com/2020/10/20201006-roskill.html (accessed: 13.05.2023).
12. Galeeva E.V., Kudryashov N.M. Rare-metal pegmatite deposits of the Kolmozero-Voronya greenstone belt (Kola region). In: *Proceedings of the Fersman Scientific Session of the GI KSC RAS*. Apatity: Geological Institute of the Kola Science Center of the Russian Academy of Sciences, 2022. P. 37—41. (In Russ.). https://doi.org/10.31241/FNS.2022.19.007
Галеева Е.В., Кудряшов Н.М. Редкометальные пегматитовые месторождения зеленокаменного пояса Колмозеро-Воронья (Кольский регион). В сб.: *Труды Ферсмановской научной сессии ГИ КНЦ РАН*. Апатиты: Геологический институт Кольского научного центра Российской академии наук, 2022. С. 37—41. https://doi.org/10.31241/FNS.2022.19.007

13. Dessemond C., Soucy G., Harvey J.P., Ouzilleau P. Phase transitions in the α—γ—β spodumene thermodynamic system and impact of γ-spodumene on the efficiency of lithium extraction by acid leaching. *Minerals*. 2020; 10(6):98-107. http://dx.doi.org/10.3390/min10060519
14. Alhadad M.F., Oskierski H.C., Chischi J., Senanayake G., Dlugogorski B.Z. Lithium extraction from β-spodumene: A comparison of keatite and analcime processes. *Hydrometallurgy*. 2023;215:15-23. https://doi.org/10.1016/j.hydromet.2022.105985
15. Salakjani N.Kh., Singh P., Nikoloski A.N. Acid roasting of spodumene: Microwave vs. conventional heating. *Minerals Engineering*. 2019;138:161—167. https://doi.org/10.1016/j.mineng.2019.05.003
16. Morozova L.N., Bazai A.V. Spodumene is the main source of lithium in rare-metal pegmatites of the Kolmozerskoe deposit. In: *Proceedings of the Fersman Scientific Session of the GI KSC RAS*. Apatity: Geological Institute of the Kola Science Center of the Russian Academy of Sciences, 2022. P. 369—373. (In Russ.). https://doi.org/10.31241/FNS.2020.17.070
Морозова Л.Н., Базай А.В. Сподумен — основной источник лития редкометалльных пегматитов Колмозерского месторождения. В сб.: *Труды Ферсмановской научной сессии ГИ КНЦ РАН*. Апатиты: Геологический институт Кольского научного центра Российской академии наук, 2022. С. 369—373. https://doi.org/10.31241/FNS.2020.17.070
17. Yunfeng S., Tianyu Z., Lihua H., Zhongwei Z., Xuheng L., A promising approach for directly extracting lithium from α-spodumene by alkaline digestion and precipitation as phosphate. *Hydrometallurgy*. 2019;189: 68—75. https://doi.org/10.1016/j.hydromet.2019.105141
18. Rezaee M., Han Sh., Sagzhanov D., Hassas B.V, Slawecki T.M., Agrawal D., Akbari H., Mensah-Biney R. Microwave-assisted calcination of spodumene for efficient, low-cost and environmentally friendly extraction of lithium. *Powder Technology*. 2022;397:115—132. https://doi.org/10.1016/j.powtec.2021.11.036
19. Quartarolli L., Brandão B., Silveira A., Nakamura M., Toma H. Improving the lithium recovery using leached beta-spodumene residues processed by magnetic nanohydrometallurgy. *Minerals Engineering*. 2022;186:223-241. https://doi.org/10.1016/j.mineng.2022.107747
20. Nobuyuki M., Shoki K., Eiji M. Microwave-based extractive metallurgy to obtain pure metals: A review. *Cleaner Engineering and Technology*. 2021;5:13—28. https://doi.org/10.1016/j.clet.2021.100306
21. Zhu Y., Zhang D., Qiu S., Liu C., Yu J., Can J. Lithium recovery from pretreated α-spodumene residue through acid leaching at ambient temperature. *Canadian Journal of Chemical Engineering*. 2023;101(8):4360—4373. https://doi.org/10.1002/cjce.24806
22. Yoğurtcuoğlu E. Investigation of the effect of cyanidation after microwave roasting treatment on refractory gold/silver ores by characterization studies. *Physicochemical Problems of Mineral Processing*. 2023;59(1):14—21. https://doi.org/10.37190/ppmp/157487
23. Fureev I.L., Neradovsky Yu. N. Choice of rational technology for processing ore from the Kolmozerskoe deposit based on the study of the chemical and mineral composition of the ore-gathering sample. In: *Proceedings of the Kola Scientific Center of the Russian Academy of Sciences. Series: Engineering sciences*. 2023;14(1):245—249. (In Russ.). http://dx.doi.org/10.37614/2949-1215.2023.14.1.044
Фуреев И. Л., Нерадовский Ю. Н. Выбор рациональной технологии переработки руды Колмозерского месторождения на основе изучения химического и минерального составов рудоразборной пробы. *Труды Кольского научного центра РАН. Сер.: Технические науки*. 2023;14(1):245—249. http://dx.doi.org/10.37614/2949-1215.2023.14.1.044
24. Tadesse B., Makuei F., Albijanic B., Dyer L. The beneficiation of lithium minerals from hard rock ores: A review. *Minerals Engineering*. 2019;131:170—184. https://doi.org/10.1016/j.mineng.2018.11.023
25. Volpi M., Pirola C., Rota C., Joaquim A., Carnaroglio D. Microwave-assisted sample preparation of α-spodumene: A simple procedure for analysis of a complex sample. *Minerals Engineering*. 2022;187:33—42. http://dx.doi.org/10.1016/j.mineng.2022.107820

Information about the authors

Olga N. Krivolapova – Cand. Sci. (Eng.), Associate Professor of the Department of Nonferrous Metals and Gold, National University of Science and Technology "MISIS".
https://orcid.org/0000-0002-5055-9430
E-mail: onk@misis.ru

Ilya L. Fureev – Head of the Department of the Laboratory for the Complex Processing of Ore Raw Materials, State Research and Design Institute of Rare Metal Industry (JSC "Giredmet").
https://orcid.org/0009-0007-7674-526X
E-mail: ifureev@mail.ru

Информация об авторах

Ольга Николаевна Криволапова – к.т.н., доцент кафедры цветных металлов и золота, Национальный исследовательский технологический университет «МИСИС».
https://orcid.org/0000-0002-5055-9430
E-mail: onk@misis.ru

Илья Леонидович Фуреев – руководитель направления лаборатории комплексной переработки рудного сырья, Государственный научно-исследовательский и проектный институт редкометаллической промышленности (АО «Гиредмет»).
https://orcid.org/0009-0007-7674-526X
E-mail: ifureev@mail.ru

Contribution of the authors

O.N. Krivolapova – determined the purpose of the work, supervised the experiments, wrote the article.

I.L. Fureev – prepared mixtures and initial samples, conducted laboratory experiments, participated in the discussion of the results.

Вклад авторов

О.Н. Криволапова – определение цели работы, руководство экспериментами, написание текста статьи.

И.Л. Фуреев – подготовка смеси и исходных образцов, проведение лабораторных экспериментов, участие в обсуждении результатов.

The article was submitted 04.09.2023, revised 08.10.2023, accepted for publication 10.10.2023

Статья поступила в редакцию 04.09.2023, доработана 08.10.2023, подписана в печать 10.10.2023