METALLURGY OF NON-FERROUS METALS / МЕТАЛЛУРГИЯ ЦВЕТНЫХ МЕТАЛЛОВ

UDC 546.74:66.081
https://doi.org/10.17073/0021-3438-2025-3-37-43

Research article
Научная статья

Assessment of the prospects for processing oxidized nickel ores using microwave energy

S.E. Polygalov, V.G. Lobanov, D.S. Sedelnikova, O.B. Kolmachikhina, O.Yu. Makovskaya

Ural Federal University n.a. the First President of Russia B.N. Yeltsin
19 Mira Str., Ekaterinburg 620002, Russia

✉ Sergei E. Polygalov (sergey.polygalov@urfu.ru)

Abstract: The Ural region holds an estimated 1.5 million tons of nickel reserves, located in the industrially developed Chelyabinsk, Sverdlovsk, and Orenburg regions. At present, however, these deposits are not being exploited, and metallic nickel is not produced in the Urals, as metallurgical facilities have been completely shut down. The reserves are represented by oxidized nickel ores (ONO) – a complex raw material with low nickel and cobalt contents, whose processing by existing technologies is economically unfeasible. The challenge is compounded by the absence of a beneficiation method for ONO that yields a concentrate; therefore, all current technologies require processing the entire ore mass, which results in high reagent consumption and substantial energy costs. Research is ongoing to develop new technological approaches, including alternative methods for extracting nickel and cobalt from ONO in the Ural deposits. One promising option is the use of microwave (MW) energy to unlock nickel-bearing minerals and accelerate the dissolution of nickel and cobalt. This study evaluates the effect of microwave energy on nickel recovery from oxidized nickel ores of the Ural region. Comparative data are presented for conventional sulfuric acid leaching and for the process with microwave energy applied. A series of test studies was carried out to assess the feasibility of using microwave energy for ONO processing. The comparison of technological parameters demonstrated the advantage of atmospheric sulfuric acid leaching with microwave energy, which achieved nickel recovery of up to 95 % in a relatively short time. These results identify this approach as the most promising for practical implementation.

Keywords: microwave energy, oxidized nickel ores, leaching, sulfuric acid, nickel.

For citation: Polygalov S.E., Lobanov V.G., Sedelnikova D.S., Kolmachikhina O.B., Makovskaya O.Yu. Assessment of the prospects for processing oxidized nickel ores using microwave energy. *Izvestiya. Non-Ferrous Metallurgy*. 2025;31(3):37–43.
https://doi.org/10.17073/0021-3438-2025-3-37-43

Оценка перспективности переработки окисленных никелевых руд с использованием СВЧ-энергии

С.Э. Полыгалов, В.Г. Лобанов, Д.С. Седельникова, О.Б. Колмачихина, О.Ю. Маковская

Уральский федеральный университет имени первого Президента России Б.Н. Ельцина
Россия, 620002, г. Екатеринбург, ул. Мира, 19

✉ Сергей Эдуардович Полыгалов (sergey.polygalov@urfu.ru)

Аннотация: Урал обладает запасами никеля на уровне 1,5 млн т. Месторождения находятся в промышленно развитом регионе – на территории Челябинской, Свердловской и Оренбургской областей. Однако в настоящее время их не разрабатывают, и металлический никель на Урале не производят, так как металлургические предприятия полностью остановлены. Причиной является то, что запасы никеля представлены окисленными никелевыми рудами (ОНР), которые являются сложным сырьем с низким содержанием никеля и кобальта, переработка которого по существующим технологиям нерентабельна. Осложняет задачу и то, что на сегодняшний день не существует метода обогащения ОНР с получением концентрата, поэтому все технологии предусматривают переработку всей массы руды, что ведет к значительным расходам на реагенты и энергетическим затратам. В то же время не прекращается поиск новых технологических подходов, ориентированных на применение альтернативных вариантов извлечения никеля и кобальта из ОНР уральских месторождений. Одним из подобных методов является применение СВЧ-энергии для вскрытия никелевых минералов и интенсификации перевода в раствор никеля и кобальта. В настоящей работе оценено влияние воздействия СВЧ-энергии на извлечение никеля из окисленных никелевых руд Уральского региона. Приводятся данные по сравнению показателей классического серно-кислотного выщелачивания и процесса с наложением СВЧ-энергии. Выполнен комплекс тестовых исследований, цель которых – оценить перспективность применения СВЧ-энергии для переработки ОНР. Сравнение технологических параметров обоих подходов выявило преимущество атмосферного серно-кислотного выщелачивания ОНР с наложением СВЧ-энергии, в ходе которого было достигнуто извлечение никеля в раствор до 95 % за небольшой промежуток времени. На основании полученных результатов данное направление выбрано как наиболее перспективное для практической реализации.

Ключевые слова: СВЧ-энергия, окисленные никелевые руды, выщелачивание, серная кислота, никель.

Для цитирования: Полыгалов С.Э., Лобанов В.Г., Седельникова Д.С., Колмачихина О.Б., Маковская О.Ю. Оценка перспективности переработки окисленных никелевых руд с использованием СВЧ-энергии. *Известия вузов. Цветная металлургия*. 2025;31(3):37–43. https://doi.org/10.17073/0021-3438-2025-3-37-43

Introduction

In both global and domestic practice, nickel is extracted from sulfide and oxidized ores. Sulfide ores are subjected to flotation beneficiation, and the resulting flotation concentrate is processed by pyrometallurgical methods [1]. Oxidized (lateritic) ores account for 60—70 % of the world's nickel reserves. These ores cannot be beneficiated by conventional methods, and nickel extraction directly from raw ore is associated with high specific costs. Therefore, the search for efficient technologies for processing oxidized nickel ores (ONO) remains highly relevant [2—4]. Abroad, laterite ore processing is generally carried out by hydrometallurgical or combined methods [5—8].

Hydrometallurgical technologies implemented in practice for ONO processing are based on direct leaching of nickel and cobalt with sulfuric acid in two main variants:

— heap leaching of raw ore with sulfuric acid solutions [9—12];

— high-pressure acid leaching under autoclave conditions (HPAL) [13;14].

In some cases, heap leaching is combined with autoclave leaching to reduce specific costs: raw ore is subjected to pressure leaching, while the residue from the autoclave stage is processed by heap leaching.

The main challenges in applying hydrometallurgical technologies to ONO from the Ural region stem from the low contents of valuable components (nickel and cobalt). The specific mineralogical features of these ores result in high reagent consumption, low recovery of target metals, and the formation of large volumes of solid waste requiring disposal. These factors render traditional hydrometallurgical technologies economically unfeasible and hinder the adaptation of foreign processing schemes to domestic ores.

It is known that in ONO, most nickel occurs as an isomorphic substitute for iron in poorly soluble silicate minerals [14]. To intensify solid—liquid reactions, elevated temperatures, pressure, and vigorous mixing are used.

The greatest potential for accelerating hydrometallurgical interactions under optimal reagent conditions in liquid—solid systems lies in enhancing mass transfer. Various approaches have been proposed to accelerate heterogeneous solid—liquid processes, including the application of oscillations of different frequencies — acoustic and ultrasonic waves, industrial-frequency current, as well as high and ultra-high frequencies.

Microwave (MW) energy is widely applied across diverse industries such as petrochemistry, agriculture, food processing, wood drying, medicine, and others. In these applications, it is generally used solely for accelerated heating of materials. Only in petrochemistry and catalytic chemistry has microwave energy been applied to intensify mass transfer processes.

The aim of the present work is to evaluate the potential for intensifying acid leaching of nickel from oxidized ore by applying microwave energy to the reaction mass and to compare the results with those of conventional nickel leaching methods..

Research methods and results

The object of study was an increment of oxidized nickel ore from the Ural region. The increments were composited, and a laboratory sample was prepared and ground to a particle size below 0.074 mm. Phase analysis revealed that the main minerals in the ore were goethite ($Fe(OH)_2 \cdot nH_2O$), silica (SiO_2), and nickel silicate ($NiO_2 \cdot SiO_2$). In addition, alumina (Al_2O_3), manganese hydroxides, calcium compounds, and other phases were present. Alumina and silica constituted the basis of the clay-forming minerals. According to chemical analysis, the ore contained (wt. %): Ni — 0.92, Co — 0.064, and Fe — 39.32.

To investigate the effect of microwave irradiation on ONO, a laboratory unit was assembled based on a commercially available inverter-type microwave oven, which maintains constant output power during operation. This allowed more accurate evaluation of specific energy consumption and minimized pulp overheating.

The pulp (ore mixed with acidic solution) was placed in a heat-resistant laboratory beaker and set inside the microwave oven directly over the waveguide outlet. To achieve this configuration, the oven was oriented vertically. To evaluate the effect of microwave irradiation, it was necessary to ensure that the entire microwave energy generated by the magnetron was focused on the reaction mass. For this purpose, the beaker was wrapped in an aluminum foil shield. These methodological arrangements allowed reliable determination of specific energy consumption, optimal pulp layer thickness (i.e., effective penetration depth of microwave energy), and the overall efficiency of the method.

A schematic of the laboratory setup is presented in Fig. 1.

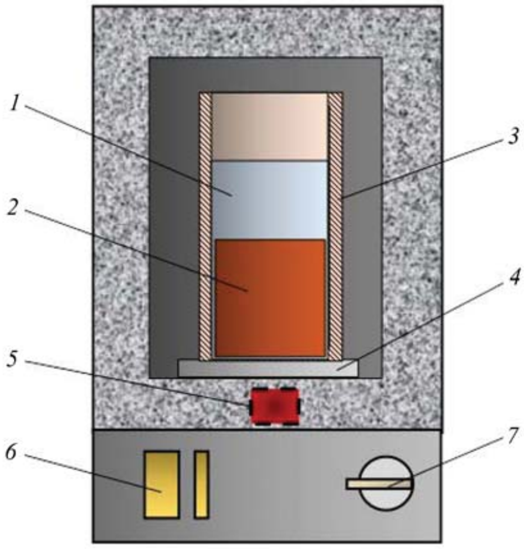

Fig. 1. Schematic of the laboratory setup

1 – reaction beaker, *2* – pulp, *3* – aluminum foil shield, *4* – support for the reaction beaker made of microwave-transparent material, *5* – magnetron, *6* – timer, *7* – power controller

Рис. 1. Схема лабораторной установки

1 – реакционный стакан, *2* – пульпа, *3* – экранирующий кожух, *4* – подставка под реакционный стакан из СВЧ-прозрачного материала, *5* – магнетрон, *6* – датчик времени, *7* – регулятор управления

Concentrated sulfuric acid solutions (≥80 g/dm^3) were used in the experiments, heated directly by microwave irradiation. To protect the magnetron from thermal and chemical effects of the reaction mass, the waveguide outlet was additionally covered with a screen made of mica and asbestos, both transparent to microwaves.

At the first stage, the effect of microwave energy on the kinetics of nickel leaching was examined by conducting comparative tests under identical conditions: liquid-to-solid ratio (L/S) = 5 : 1, stirring intensity 400 rpm, temperature ≤75 °C, and H_2SO_4 concentration 200 g/dm^3. Parallel ore charges of equal mass were leached in a beaker on a conventional heating plate and in the microwave-assisted setup. Microwave activation was performed at an output power of 180 W for 20 min in both cases.

At specified time intervals, aliquots of the pregnant solution were withdrawn and analyzed for nickel content by atomic absorption spectroscopy (Analytik Jena, Germany). Nickel recovery into solution was then calculated (Fig. 2).

As expected, microwave irradiation significantly accelerated nickel dissolution compared with conventional thermal leaching, increasing the leaching rate by approximately fourfold. Although the maximum achievable nickel recovery was not determined in this series, the observed trend suggests that microwave activation substantially shortens the time required to achieve high extraction.

For practical implementation of the proposed method and reactor design, it was important to estimate the penetration depth of microwave energy into the solid—liquid system (a pulp consisting of sulfuric acid solution and ground ore at a liquid-to-solid ratio of 1 : 1). To vary the pulp layer thickness, different volumes of pulp were loaded into the reaction vessel. A separate beaker containing a fixed volume of distilled

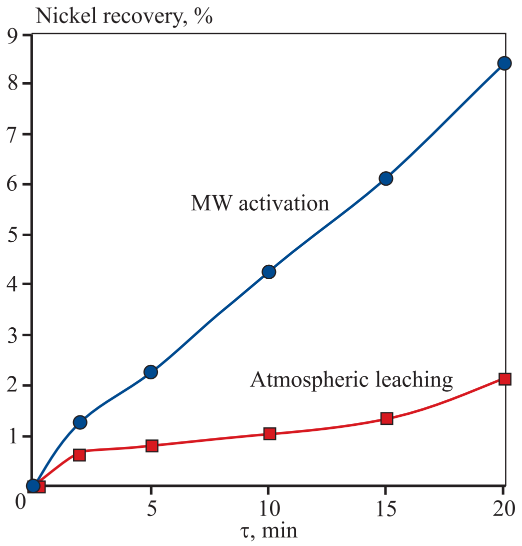

Fig. 2. Nickel recovery as a function of time under microwave-assisted and atmospheric leaching of ONO

Рис. 2. Сравнение динамики выщелачивания никеля из ОНР

water was placed above the reaction vessel. When the microwave oven was switched on, the extent of heating of the water indicated the fraction of microwave energy that had not been absorbed by the pulp. Thus, by comparing the temperature rise in the water at different pulp heights, the penetration depth of the microwave energy flux through the reaction mass was assessed. The chosen pulp density (L/S = 1 : 1) minimized particle settling during the test, ensuring reliable evaluation of microwave penetration depth.

The absorbed energy was calculated from the temperature difference before and after irradiation according to the equation:

$$E = \frac{mC\Delta t}{\tau},$$

where E is the absorbed energy, W/s; m is the mass of water, g; C = 4.18 J/g·°C is the specific heat capacity of water; Δt is the temperature difference, °C; and τ is time, s.

The amount of microwave energy absorbed by the reaction mass at different layer thicknesses is presented in the table.

The results show that in dense pulp, the microwave flux is fully absorbed within a 4—6 cm layer. Naturally, this parameter depends on microwave power, pulp density, and mixing conditions. The penetration depth of microwave energy — where heating occurs and reactions are intensified — is referred to as the effective microwave depth. Within this zone, heating, the skin effect, and accelerated dissolution of target metals can be expected.

In the next stage, the effect of specific sulfuric acid consumption on nickel leaching was evaluated. Since an additional aim was to estimate the maximum achievable recovery, experiments were performed at maximum magnetron power (900 W) with deliberately excess acid addition.

The leaching solution was prepared by dissolving the required mass of acid in water and diluting to a fixed volume. Ore charges weighed 30 g, and the solution volume was 60 ml. At this power, the reaction mass rapidly evaporated, forming a dense sinter that fundamentally altered the process. To avoid this, the experiment duration was limited to 4 minutes. Monitoring the temperature of the reaction mass during microwave activation was not feasible; post-experiment measurements showed that under steady-state conditions the temperature rapidly reached 95—100 °C.

Given the expected high reaction rate between nickel-bearing minerals and sulfuric acid, the acid concentration was the critical factor in the leaching process. To enable proper comparison of experimental results at equal slurry volumes (effective layer thickness of 4 cm) and different acid concentrations, the specific acid consumption was varied from 0.4 to 2.0 g H_2SO_4 per gram of ore.

The ore charges were mixed with sulfuric acid solution and subjected to microwave irradiation for a set leaching time (e.g., 1 min). The pulp was then removed, diluted with water, filtered, and the filtrate analyzed for nickel concentration and residual acid. Leaching was repeated at the same acid consumption but with different leaching times. Thus, each point on the curves in Figs. 3 and 4 corresponds to a separate test. For comparison, additional experiments at 2 g H_2SO_4 per g ore were performed by heating the pulp to 95 °C without microwave activation. Based on these results, nickel recovery into solution and the fraction of sulfuric acid consumed in the target reaction were calculated.

Microwave energy absorbed by the reaction mass at different pulp layer heights

Количество СВЧ-энергии, поглощенной реакционной массой при разной высоте слоя пульпы

Pulp height , mm	Absorbed energy, J	Energy loss, %
10	253.6	71.8
20	612.3	32.0
40	891.4	1.0
60	895.1	0.5

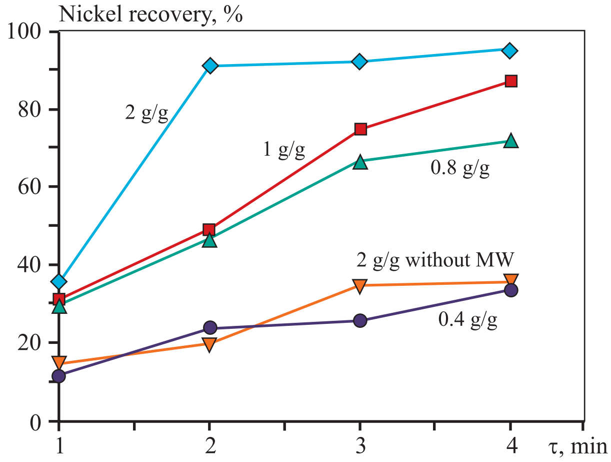

Fig. 3. Dependence of nickel recovery on sulfuric acid consumption under microwave-assisted leaching of ONO (g/g ore)

Рис. 3. Зависимость извлечения Ni в раствор при выщелачивании с наложением СВЧ-энергии при различном расходе серной кислоты (г/г руды)

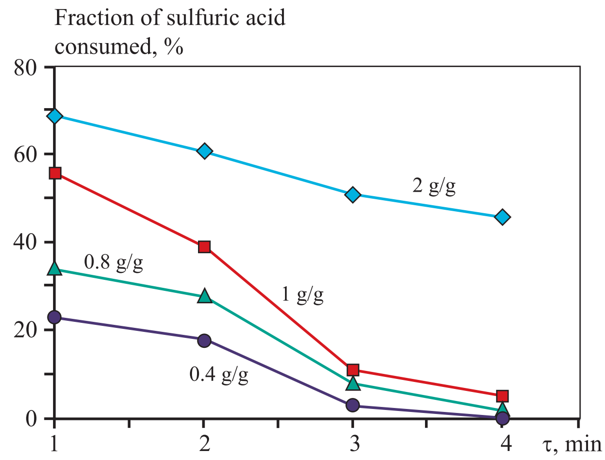

Fig. 4. Dependence of sulfuric acid consumption on time under microwave-assisted leaching of ONO (g/g ore)

Рис. 4. Зависимость расхода серной кислоты при СВЧ-выщелачивания ОНР (г/г руды)

The results show that under excess (i.e., high concentration of) sulfuric acid, the nickel leaching rate under microwave activation increased severalfold compared with conventional methods.

The experiments were not aimed at determining reagent consumption coefficients or performing an economic assessment of this approach, but the results demonstrate that under certain conditions, near 100 % nickel recovery can be achieved in a very short time. With countercurrent leaching — widely used in hydrometallurgy — this method could achieve the required metal recovery at high rates. Overall, the findings confirm the potential of microwave energy for enhancing the efficiency of metallurgical ore processing.

Further studies will focus on the features of microwave-assisted leaching of oxidized nickel ore under countercurrent liquid—solid conditions.

Conclusions

1. An original methodology was proposed for studying metal leaching from mineral raw materials using microwave energy.

2. It was established that the effective penetration depth of microwave energy through a dense solid—liquid system (“ground ore — leaching solution”) at a liquid-to-solid ratio of 1 : 1 does not exceed 40 mm.

3. Atmospheric sulfuric acid leaching of ONO with microwave activation was shown to accelerate the process severalfold, achieving up to 95 % nickel recovery into solution.

References

1. Peiyu Zhang, Qiang Guo, Guangye Wei, Long Meng, Linxin Han, Jingkui Qu, Tao Qi. Extraction of metals from saprolitic laterite ore through pressure hydrochloric-acid selective leaching. *Hydrometallurgy*. 2015; (157):149—158. https://doi.org/10.1016/j.hydromet.2015.08.007
2. Fatahi Mohammadreza, Noaparast Mohammad, Shafaei Seyyed Ziaeddin. Nickel extraction from low grade laterite by agitation leaching at atmospheric pressure. *International Journal of Mining Science and Technology*. 2014;4:543—548. https://doi.org/10.1016/j.ijmst.2014.05.019
3. Jian-ming Gao, Mei Zhang, Min Guo. Innovative methodology for comprehensive utilization of saprolite laterite ore: Recovery of metal-doped nickel ferrite and magnesium hydroxide. *Hydrometallurgy*. 2015;(158):27—34. https://doi.org/10.1016/j.hydromet.2015.09.027
4. Pickles C.A. Microwave heating behavior of nickeliferous limonitic laterite ores. *Minerals Engineering*. 2004;6: 775—784. https://doi.org/10.1016/j.mineng.2004.01.007
5. Reid J., Barnett S. Nickel laterite hydrometallurgical processing update. In: *Nickel-Cobalt-8. Technical Sessions Proceedings «Alta Metallurgical Services»*. Perth, W. Australia, 2002. 27 p.
6. Berezowsky R.M. Laterite: new life of limonite. *Minerals Industry International*. 1997;1034:46—55.
7. Urbain D., Duterque J. P., Palanque Ph., Rey P. Economic comparison between the sulphuric acid leach process

and other processes for oxidized nickel ores. In: *Proceedings-nickel metallurgy. Vol. I: Extraction and refining of nickel*. 1986. P. 578—596.

8. Motteram G., Ryan M., Berezowsky R.M., Raudsepp R., Murrin M. Nickel-Cobalt Project: Project Development Overview. In: *Proc. of Nickel-Cobalt Pressure Leaching and Hydrometallurgy Forum* (May 13-14, 1996), Perth, Australia: Alta Metallurgical Services, 1996.
9. Alenichev V.M., Umansky A.B., Klyushnikov A.M. Physicochemical features of the process of heap leaching of oxidized nickel ores of the Urals using sulfuric acid solutions. *Vestnik Voronezhskogo universiteta*. 2013;(2):9—14.
   Аленичев В.М., Уманский А.Б., Клюшников А.М. Физико-химические особенности процесса кучного выщелачивания окисленных никелевых руд Урала с использованием растворов серной кислоты. *Вестник Воронежского университета*. 2013;(2):9—14.
10. Umansky A.B., Klyushnikov A.M. Hydrometallurgical technology of processing serpentinite dumps with the release of nickel concentrate. In: *Proceedings of the International Congress "Fundamentals of technologies for processing and utilization of technogenic waste"* (June 14–16 2012). Yekaterinburg: Уральский издательский полиграфический центр, P. 419–422.
   Уманский А.Б., Клюшников А.М. Гидрометаллургическая технология переработки отвалов серпентинита с выделением никелевого концентрата. В сб.: *Труды международного конгресса «Фундаментальные основы технологий переработки и утилизации техногенных отходов»*. 2012.
11. McDonald R.G., Whittington B.I. Atmospheric acid leaching of nickel laterites review. Part I. Sulphuric acid technologies. *Hydrometallurgy*. 2008;(1-4):35—55. https://doi.org/10.1016/j.hydromet.2007.11.009
12. Alenichev V.M., Umansky A.B., Klyushnikov A.M. Development of heap leaching technology for oxidized nickel ores of the Ural deposits. *Izvestiya Tomskogo politekhnicheskogo universiteta*. 2013;(3):124—128.
   Аленичев В.М., Уманский А.Б., Клюшников А.М. Разработка технологии кучного выщелачивания окисленных никелевых руд Уральских месторождений. *Известия Томского политехнического университета*. 2013;(3):124—128.
13. Naboychenko S.S., Ni L.P., Shneerson Ya.M., Chugaev L.V. Autoclave hydrometallurgy of non-ferrous metals. Yekaterinburg: Ural State Technical University–UPI, 2002. 940 p. (In Russ.).
   Набойченко С.С., Ни Л.П., Шнеерсон Я.М., Чугаев Л.В. Автоклавная гидрометаллургия цветных металлов. Екатеринбург: УГТУ—УПИ, 2002. 940 с.
14. Kolmachikhina O.B. Combined technology for processing oxidized nickel ores (using the Serovskoye deposit as an example): Diss. Cand Sci. (Eng.). Yekaterinburg: UrFU, 2018. (In Russ.).
   Колмачихина О.Б. Комбинированная технология переработки окисленных никелевых руд (на примере Серовского месторождения): Дис. на соискание ученой степени канд. техн. наук. Екатеринбург: УрФУ, 2018.

Information about the authors

Sergei E. Polygalov – Senior Lecturer at the Department of non-ferrous metallurgy (NFM), Ural Federal University n.a. the First President of Russia B.N. Yeltsin (UrFU).
E-mail: sergey.polygalov@urfu.ru

Vladimir G. Lobanov – Cand. Sci. (Eng.), Associate Professor of the Department of NFM, UrFU.
https://orcid.org/0000-0001-6450-8434
E-mail: lobanov-vl@yandex.ru

Dar'ya S. Sedelnikova – Student of the Department of NFM, UrFU.
E-mail: Daria.Sedelnikova@urfu.me

Ol'ga B. Kolmachikhina – Cand. Sci. (Eng.), Associate Professor of the Department of NFM, UrFU.
https://orcid.org/0000-0002-7879-8791
E-mail: o.b.kolmachikhina@urfu.ru

Ol'ga Yu. Makovskaya – Cand. Sci. (Eng.), Associate Professor of the Department of NFM, UrFU.
E-mail: o.i.makovskaia@urfu.ru

Информация об авторах

Сергей Эдуардович Полыгалов – ст. преподаватель кафедры металлургии цветных металлов (МЦМ), Уральский федеральный университет имени первого Президента России Б.Н. Ельцина (УрФУ).
E-mail: sergey.polygalov@urfu.ru

Владимир Геннадьевич Лобанов – к.т.н., доцент кафедры МЦМ, УрФУ.
https://orcid.org/0000-0001-6450-8434
E-mail: lobanov-vl@yandex.ru

Дарья Сергеевна Седельникова – студент кафедры МЦМ, УрФУ.
E-mail: lev.sokolov@urfu.ru

Ольга Борисовна Колмачихина – к.т.н., доцент кафедры МЦМ, УрФУ.
https://orcid.org/0000-0002-7879-8791
E-mail: o.b.kolmachikhina@urfu.ru

Ольга Юрьевна Маковская – к.т.н., доцент кафедры МЦМ, УрФУ.
E-mail: o.i.makovskaia@urfu.ru

Contribution of the authors

S.E. Polygalov – development of the main concept, definition of research objectives and tasks, preparation of the manuscript, formulation of conclusions.

V.G. Lobanov – scientific supervision, revision of the manuscript and conclusions.

D.S. Sedelnikova – experiment preparation and experimental work.

O.B. Kolmachikhina – calculations and preparation of the manuscript.

O.Yu. Makovskaya – calculations and analysis of research results.

Вклад авторов

С.Э. Полыгалов – формирование основной концепции, постановка цели и задачи исследования, подготовка текста, формулировка выводов.

В.Г. Лобанов – научное руководство, корректировка текста и выводов.

Д.С. Седельникова – подготовка и проведение экспериментов.

О.Б. Колмачихина – осуществление расчетов, подготовка текста статьи.

О.Ю. Маковская – проведение расчетов, анализ результатов исследований.

The article was submitted 12.05.2025, revised 23.05.2025, accepted for publication 29.05.2025

Статья поступила в редакцию 12.05.2025, доработана 23.05.2025, подписана в печать 29.05.2025