**Динара Мұқталы** – PhD, Жану проблемалары институты аға ғылыми қызметкері; e-mail: dinara.muktaly@mail.ru. ORCID: https://orcid.org/0000-0002-1139-5488.
**Анар Шынабайқызы Аккенжеева** – т.ғ.к., қауымдастырылған профессор, Ш. Есенов атындағы Каспий технологиялар және инжиниринг университеті мұнайхимиялық инжиниринг кафедрасы доценты; e-mail: anar.akkenzheyeva@yu.edu.kz. ORCID: https://orcid.org/0000-0002-9847-8218.
**Аккенже Чаншарқызы Бусурманова** – х.ғ.к., қауымдастырылған профессор, Ш. Есенов атындағы Каспий технологиялар және инжиниринг университеті жаратылыстану ғылымдары кафедрасы доценты; e-mail: akkenzhe.bussurmanova@yu.edu.kz. ORCID: https://orcid.org/0000-0001-8228-7188.

**Information about the authors**

**Yerzhan Imanbaiuly Imanbayev*** – PhD, Associate Professor, Leading Researcher at Institute of Combustion Problems; e-mail: erzhan.imanbayev@mail.ru. ORCID: https://orcid.org/0000-0001-8273-0020.
**Akbota Kairatkyzy Serikkazinova** – Junior Researcher at Institute of Combustion Problems; e-mail: akbota.serikkazinova@mail.ru. ORCID: https://orcid.org/0009-0009-2554-1616.
**Dinara Muktaly** – PhD, Senior Researcher at Institute of Combustion Problems; e-mail: dinara.muktaly@mail.ru. ORCID: https://orcid.org/0000-0002-1139-5488.
**Anar Shynabaevna Akkenzheeva** – Candidate of Technical Sciences, Associate Professor of the Department of Petrochemical Engineering of the Yessenov University; e-mail: anar.akkenzheyeva@yu.edu.kz. ORCID: https://orcid.org/0000-0002-9847-8218.
**Akkenzhe Chansharovna Bussurmanova** – Candidate of Chemical Sciences, Associate Professor of the Department of Natural Sciences of the Yessenov University; e-mail: akkenzhe.bussurmanova@yu.edu.kz. ORCID: https://orcid.org/0000-0001-8228-7188.

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**B. Rakhadilov[1], E. Shayakhmetov[2], Zh. Bakyt[2], S. Buresh[2], N. Musataeva[2]***
[1]Plasma Science LLP,
Ust-Kamenogorsk 070000, Kazakhstan
[2]Engineering Center «Strengthening Technologies and Coatings», Shakarim University,
Semey 071412, Kazakhstan
*e-mail: naziramusataeva51@gmail.com

## STUDY OF THE INFLUENCE OF HEATING DURATION DURING ELECTROLYTIC-PLASMA HARDENING ON THE CHARACTERISTICS OF 20GL STEEL

***Abstract:*** *This article presents a comprehensive examination of the electrolytic-plasma hardening (EPH) process applied to 20GL structural steel, a material frequently used in the automotive, transport, and various other industries. The relevance behind this research lies in the necessity to enhance the performance of steels that face high mechanical loads, elevated temperatures, and corrosive environments. Experimental findings reveal that electrolytic-plasma treatment substantially increases the hardness of 20GL steel to approximately 600 HV on average. Additionally, prolonging the heating duration contributes significantly to greater hardness, playing a decisive role in bolstering wear resistance under load. Microstructural analysis confirms the formation of a fine-grained martensitic phase, highlighting the steel's transformation and strengthening. Furthermore, the study emphasizes that the chemical composition of 20GL steel influences the hardness gradient from the surface inward and leads to the development of finer-grained features in the steel's microstructure. Overall, the electrolytic-plasma process proves beneficial not only for improving mechanical attributes but also for enhancing reliability and service life of critical components. From an industrial standpoint, this technology is notable for its adaptability and cost-effectiveness, making it an attractive solution for sectors such as automotive manufacturing, construction, and the energy industry. Thus, electrolytic-plasma hardening emerges as a forward-looking method aligned with modern engineering demands, offering a promising avenue for advanced material optimization.*

***Key words:*** *electrolytic plasma hardening; 20GL steel; hardness; wear resistance; corrosion resistance of steel.*

## Introduction

One of the key factors influencing the demand for a designed part is its quality. The operability and reliability are ensured by meeting such basic requirements as strength, rigidity, and resistance to various influences (wear, vibration, temperature, etc.). Meeting strength requirements under static, cyclic, and impact loads should eliminate the possibility of destruction and unacceptable residual deformations. The part must be wear-resistant, as this greatly affects the durability of the mechanism's operation. The wear resistance requirement can be met not only through design solutions and the use of new high-strength materials but also by improving the surface layer of machine parts. There are several methods of surface hardening, which are classified by the principle of action: mechanical, thermal, chemical-thermal methods, methods using concentrated energy sources, diffusion saturation, and others.

Steel 20GL, used for the manufacture of cast load-bearing parts of freight railway wagons, faces several issues related to fatigue strength and brittleness. These parts operate under high loads and in various climatic conditions, requiring the material to have high fatigue resistance and resistance to brittle fracture throughout its service life. The increased requirements for the operational reliability of new freight car designs call for new approaches to ensuring the durability and fatigue crack resistance of cast steels [1-4]. A critical factor determining the longevity of a structure is the material's ability to resist the propagation of fatigue cracks, which is especially important in highly stressed areas where structural defects and stress concentrations exist [5-7]. Mechanical tests of 20GL steel under cyclic loading showed that cracks develop with an increase in the plastic zone at their tip. In the crack growth rate range of $6 \cdot 10^{-8}$ - $1.5 \cdot 10^{-6}$ m/cycle, the steel tends to gradually degrade under fatigue loads. This confirms the need for further research and improvement of technologies to increase the fatigue strength and longevity of cast load-bearing parts, especially considering the high operational loads in modern wagons [8, 9].

Surface thermal hardening of steel parts is one of the most effective ways to increase the lifespan of heavily loaded elements of machines and mechanisms while also reducing material consumption. In this process, only the most stressed working surface of the part is hardened, leaving the core intact. These technologies provide higher operational properties and hardening quality. Today, methods such as high-frequency, gas-flame, plasma, electron-beam, and laser treatment are widely used in industry for thermal treatment of critical and heavily loaded parts [10-12].

Steel 20GL is widely used for the production of side frames for freight cars, which often experience mechanical failures due to improper processing before operation.

For example, a study conducted by Chelyakh A.P. and Karavaeva N.E. [13] presented the results of thermal quenching of 20GL steel after cementation, which led to the formation of the desired microstructure and improved mechanical properties of the steel. In the study, samples were subjected to cementation at 930 °C, followed by quenching in the range of 780 to 1150 °C, and low tempering at 200 °C. The results showed that the highest surface hardness was achieved after quenching at 780°C, while at 1150°C, the hardness was minimal due to the increased content of retained austenite and decreased martensite. The highest impact-abrasive wear resistance was observed after quenching at 780-880°C. The authors note that when heated to 1150°C, wear resistance decreased, which is associated with carbide dissolution and grain growth. After cementation and thermal treatment, the wear resistance of 20GL steel increased more than six times.

Additionally, in the work of Priupolin D.V. and Budruev A.V., the results of tests on 20GL steel after volumetric surface hardening (VSH) are presented, which proved to be preferable compared to water quenching and tempering in several parameters [14]. It was found that after normalization, the steel had a ferrite-pearlite structure, and after quenching, the steel's structure transformed into martensite-like with a reduction in grain size. Volumetric surface hardening led to the formation of troostite-like structure with finer grains in the surface zone: from 0.4 to 3.8 microns, while the grains increased closer to the center of the sample. The structural change directly influenced the mechanical properties. After VSH, the steel demonstrated higher hardness and yield strength compared to normalization while maintaining increased elongation, indicating better plasticity. Thus, volumetric surface hardening of 20GL steel provides an optimal combination of hardness and plasticity, making this method preferable for producing structures subjected to dynamic loads, such as train side frames.

In another study by A.P. Chelyakh and N.E. Karavaeva [15], the description of 20GL steel after thermal cyclic quenching is provided, which also led to improved performance characteristics. After two cycles of thermal cyclic hardening, an austenite-martensite structure with a surface microhardness of about 4400 MPa was observed. With an increase in the number of cycles to 14, surface microhardness increased to 5500 MPa, and at a depth of 1-1.5 mm – up to 6500 MPa. Such a structure significantly increases the wear resistance of steel: under dry friction, the relative wear resistance reaches 3, and under abrasive wear – 2.5. The authors explain the improvements by grain refinement, austenite enrichment with carbon, and self-hardening of the steel due to the transformation of retained austenite into martensite.

Currently, the railways are facing the challenge of operational failure of the side frames of freight wagon bogies. Addressing this issue is essential to ensure safety on the railway network. In recent years, there has been statistical data on railway derailments, which occurred partly due to poor-quality components. The most serious problem today remains the low quality of cast parts of freight wagon bogies produced by wagon-building factories. All the failed side frames had been in service for no more than two to three years since their manufacture, while the manufacturers guaranteed a normative service life of 32 years. Therefore, the railway industry requires improvements in the methods of production and operation of the products used.

Among the existing hardening methods, plasma surface hardening is widely and effectively applied due to its technical and economic indicators. One of the types of plasma surface hardening is electrolytic plasma hardening (EPH). EPH is a modern metal treatment method in which the surface of the part is heated to high temperatures using an electric arc burning in the electrolyte. Simultaneously with heating, electrolysis occurs, leading to changes in the chemical composition of the surface layer of the metal. This comprehensive approach significantly improves the characteristics of steel: increasing its hardness, wear, and corrosion resistance. Moreover, the EPH technology is simple and environmentally friendly, making it attractive for a wide range of applications [16, 17].

**Research Methods**

The object of study was 20GL steel, and the samples were prepared from rolled steel by cutting into sizes of 20x20x15mm, followed by grinding and polishing. The investigation was carried out on 20GL structural steel. Specimens subjected to standardized metallographic preparation. Initial surface leveling was performed using a TROJAN GP-1A grinding machine, followed by sequential manual grinding on glass plates with silicon carbide abrasive papers ranging from P60 to P2500 grit. Final polishing was conducted on a napped cloth using a 0.5 μm chromium oxide suspension to achieve a scratch-free mirror finish suitable for microstructural analysis. EPH was carried out on an electrolytic plasma treatment unit, the design and operating principles of which are detailed in reference [18, 19]. The EPH parameters are provided in Table 1. A sodium carbonate aqueous solution with a 20% concentration was used as the electrolyte for all the samples. As shown in Table 1, the applied voltage for samples No. 1 and No. 2 was 240 V, and for the other two samples, it was 250 V. The heating time ranged from 6 to 10 seconds for different samples.

Table 1 – EPH Parameters

| Sample | Actual voltage, V | Current strength, A | Heating time, s |
|---|---|---|---|
| No 1 | 240 | 40 | 6 |
| No 2 | 240 | 40 | 8 |
| No 3 | 250 | 60 | 8 |
| No 4 | 250 | 60 | 10 |

Metallographic analysis was performed using an HL-102AW microscope with a 3.0 MP digital camera and specialized software by Altami. For metallographic microanalysis of the samples, after polishing with a chromium oxide-based paste, a 3% alcohol solution of nitric acid was used as an etchant. Microhardness measurements were conducted using a Vickers HV-1 DT tester under a load of 1 N with a 10-second dwell time, in accordance with GOST 9450-76.

To investigate the microstructure of 20GL steel after treatment by the EPU method, scanning electron microscopy (SEM) was used on a TESCAN VEGA Compact instrument. This device, in combination with energy-dispersive spectroscopy (EDS), allows for the identification of morphological features of the microstructure, indirect differentiation of phases with similar chemical compositions – such as martensite, bainite, and ferrite – based on contrast, as well as the determination of the distribution of alloying elements.

**Results and Discussion**

The microstructure of 20GL steel in its initial state contains pearlitic and ferritic inclusions, as seen in Figure 1. In the image, ferrite appears as light areas, and pearlite as dark areas, which become visible after etching with an alcohol solution of nitric acid.

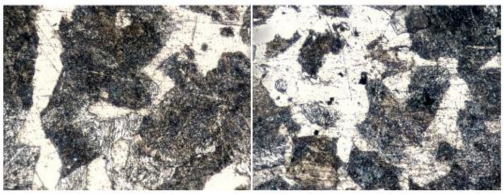

Figure 1 – Microstructure of 20GL steel before quenching

As a result of quenching, which occurs during rapid cooling from a high-temperature state, austenite transforms into martensite – a metastable phase with a characteristic fine-grained structure. Martensitic precipitates form in the form of thin, elongated crystals, which contributes to the improvement of the steel's strength properties. These precipitates have high hardness due to their rigid crystal lattice, which makes the steel more resistant to wear.

In the SEM images shown in Figure 2, obtained from a cross-section of 20GL steel samples after EPH, changes in the material's microstructure related to the temperature effects can be observed. 20GL steel contains manganese, which influences the quenching processes, and its presence affects the formation of the microstructure. However, it is important to note that while manganese positively affects hardenability, it can also lead to uneven hardness distribution in the material, as seen in these images. The images also show that the near-surface layers of the steel have a higher density and fine-grained structure, which is associated with increased hardness in these areas. With increasing depth, a decrease in density and changes in grain structure are observed, correlating with the uneven distribution of hardness. This indicates that the presence of manganese in the steel composition contributes both to improving hardenability and to the formation of areas with varying properties.

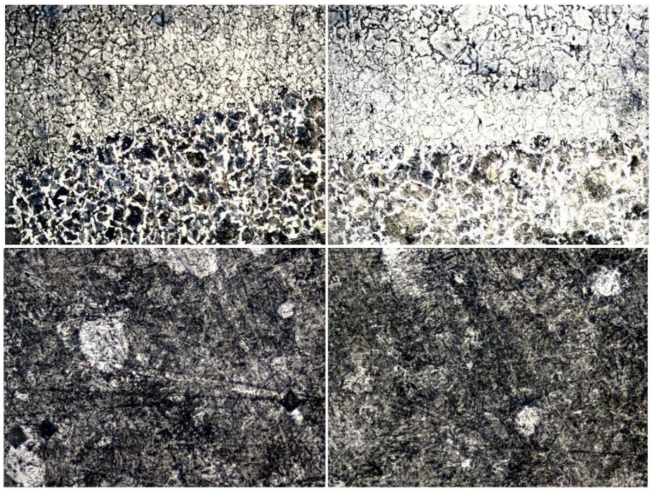

Figure 2 – Microstructure of a cross-section of 20GL hardened steel

The images clearly show the surface hardening zone, where significant structural changes have occurred due to EPH. Grain boundaries are well-defined, but in these zones, one can observe sharp changes in the microstructure, indicating uneven heat distribution throughout the volume.

Thus, SEM images and microhardness data confirm the influence of manganese on the structure of 20GL steel after EPH. Despite manganese's contribution to increasing hardenability and reducing grain growth tendency, martensite formation in 20GL steel after quenching leads to a significant increase in hardness, making it suitable for critical structures with high wear resistance requirements. Martensitic structures also help to increase tensile strength and fatigue strength, which is critically important for parts subjected to cyclic loads. However, despite these advantages, it should be noted that an increased martensite content may lead to reduced ductility and impact toughness.

These factors must be considered when designing and choosing operating conditions for steel to ensure an optimal balance of mechanical properties for specific applications [20].

Figure 3 shows SEM images of the microstructure of 20GL steel at 2000x magnification. These images clearly show structural changes that occurred as a result of EPH. The images demonstrate the characteristic microstructural features of the steel surface in different areas, allowing conclusions to be drawn about the phase and structural transformations.

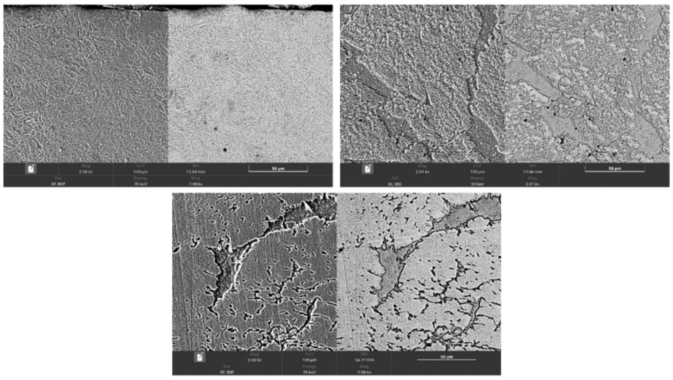

Figure 3 – The SEM images became 20 GL at 2000x magnification

The upper images show a division into zones with different microstructures. The left part of the images shows a more uniform, fine-grained structure typical of the surface layers after hardening. The right part contains larger grains, indicating a zone where the quenching process was less effective and is located further from the near-surface zone. The boundary shows clear differences in grain size, indicating a transition between the surface and inner quenching zones.

The lower images also demonstrate the steel's heterogeneous structure. Cracks and breaks in the structure can be observed, which may be a result of thermal stresses that occurred during the EPH process. These defects may result from uneven hardness distribution and changes in the steel's phase composition. The images show zones with higher density and fine-grained structure, indicating high hardness in these areas. On the right, coarse-grained areas with signs of segregation can be seen, which may be the result of differences in material cooling and phase state changes.

In Figure 4, which shows the change in the microhardness of 20GL steel with depth after EPH. According to this graph, it can be seen that the thickness of the hardened layer is greater for samples No. 2, No. 3 than for sample No. 4. According to this graph, it can be seen that sample No. 1 has a lower hardness compared to the others, but the thickness of the hardened layer is approximately the same for all samples. It is also clearly visible that the material's hardness changes unevenly across the cross-section. This indicates non-uniform quenching, likely due to the effect of manganese present in the steel's composition on the distribution of heat flow and phase transformations during hardening.

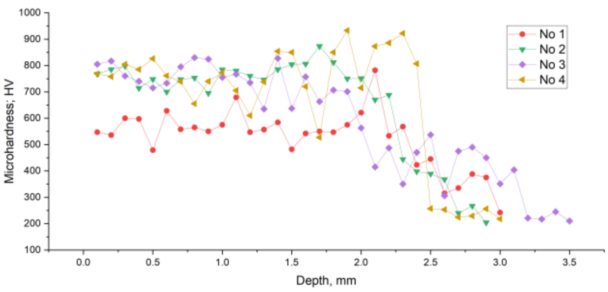


Figure 4 – Distribution of microhardness by depth after electrolytic-plasma hardening of 20GL steel samples

Manganese, which is part of 20GL steel, improves hardenability, but its action does not ensure uniform hardness distribution throughout the material's depth due to chemical and structural heterogeneities. In [21] it was said that often the microstructure after hardening began to have an unusual cross-section and, as a rule, should lead to a significant spread in the work of mechanical properties. This leads to fluctuations in hardness in different zones, especially in the range of 0.5-2.5 mm from the surface, where sharp changes are observed. These spreads may also result from the uneven distribution of phases, such as martensite and ferrite, which form during cooling after EPH treatment.

After applying EPH, there is a significant increase in microhardness, especially in the near-surface layers of the material. This effect is due to grain refinement, the formation of carbide phases, and hardening caused by the high temperatures characteristic of the EPH method. The surface layers of the steel undergo intense thermal effects, leading to microstructural changes and significantly enhancing its wear resistance and resistance to mechanical loads.

Comparing the initial and final state of 20GL steel, it can be noted that after EPH, the microhardness increases by 2.5-3 times. This indicates the high effectiveness of this hardening method, making 20GL steel much more suitable for operation under high mechanical loads and intense friction. This result significantly expands its potential for use in heavily loaded units and equipment parts, increasing their durability and reliability.

## Conclusions

The conducted research demonstrated the high efficiency of EPH of 20GL steel using sodium carbonate as an electrolyte. The treatment significantly improved the microstructure and microhardness. As a result of quenching, a hardened surface layer was formed, which increased microhardness to 600 HV, representing a 2.5-3 fold increase compared to the initial values. The results suggest that EPH is a promising and effective method for hardening 20GL steel, significantly extending its durability under high mechanical and abrasive load conditions. Considering the above, this method can be recommended for application in various industries, including the production of machine and mechanism parts operating under high loads and in aggressive environments. These results open opportunities for further application and optimization of the technology in industry, which will significantly increase the service life and reliability of products made from 20GL steel.

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**Б.К. Рахадилов[1], Е.Я. Шаяхметов[2], Ж.Ә. Бақыт[2], С.И. Буреш[2], Н.Е. Мусатаева[2]***
[1]ЖШС «Plasma Science»,
070000, Қазақстан, Өскемен қ.
[2]Инжиниринг орталығы «Қатайту технологиялары және жабындар», Шәкәрім университеті,
071412, Қазақстан, Семей
*e-mail: naziramusataeva51@gmail.com

## ЭЛЕКТРОЛИТТІ-ПЛАЗМАЛЫҚ БЕРІКТЕНДІРУ КЕЗІНДЕГІ ҚЫЗДЫРУ ҰЗАҚТЫҒЫНЫҢ 20ГЛ БОЛАТТЫҢ СИПАТТАМАЛАРЫНА ӘСЕРІН ЗЕРТТЕУ

*Бұл мақалада автомобиль, көлік және басқа да салаларда жиі қолданылатын 20ГЛ құрылымдық болатқа қолданылатын электролиттік-плазмалық беріктендіру (ЭПБ) процесін кешенді зерттеу ұсынылған. Бұл зерттеудің мотивациясы жоғары механикалық жүктемелерге, жоғары температураға және коррозиялық ортаға ұшырайтын болаттардың пайдалану сипаттамаларын арттыру қажеттілігі болып табылады. Эксперименттік дәлелдер электролиттік плазмалық өңдеу 20ГЛ болатының қаттылығын орта есеппен 600HV-ге дейін айтарлықтай арттыратынын көрсетеді. Сонымен қатар, қыздыру ұзақтығының артуы қаттылықтың жоғарылауына айтарлықтай ықпал етеді, жүктеме кезінде тозуға төзімділікті арттыруда шешуші рөл атқарады. Микроқұрылымдық талдау болаттың трансформациясы мен қатаюына баса назар аудара отырып, ұсақ түйіршікті мартенсит фазасының түзілуін растайды. Сонымен қатар, зерттеу 20ГЛ болат химиясы бетінен ішке қарай қаттылық градиентіне әсер ететінін және болаттың микроқұрылымында ұсақ түйіршікті ерекшеліктердің дамуына әкелетінін атап көрсетеді. жалпы, электролит-плазмалық процесс механикалық өнімділікті жақсарту үшін ғана емес, сонымен қатар маңызды компоненттердің сенімділігі мен қызмет ету мерзімін жақсарту үшін де пайдалы. Өнеркәсіптік тұрғыдан алғанда, бұл технология өзінің бейімделгіштігімен және экономикалық тиімділігімен ерекшеленеді, бұл оны автомобиль, құрылыс және энергетика сияқты секторлар үшін тартымды шешім етеді. Осылайша, электролитті-плазмалық қатайту заманауи инженерлік талаптарға сәйкес келетін перспективалық әдіске айналады, бұл материалдарды жетілдірілген оңтайландырудың перспективалы жолын ұсынады.*

***Түйін сөздер:*** *электролит-плазмалық беріктендіру, 20ГЛ болат, қаттылық, тозуға төзімділік, болаттың коррозияға төзімділігі.*

**Б.К. Рахадилов[1], Е.Я. Шаяхметов[2], Ж.Ә. Бақыт[2], С.И. Буреш[2], Н.Е. Мусатаева[2*]**
[1]ТОО «Plasma Science»,
070000, Казахстан, г. Усть-Каменогорск,
[2]Инжиниринговый центр «Упрочняющие технологий и покрытия», Шәкәрім университет,
071412, Республика Казахстан, г. Семей
*e-mail: naziramusataeva51@gmail.com

**ИССЛЕДОВАНИЕ ВЛИЯНИЯ ПРОДОЛЖИТЕЛЬНОСТИ НАГРЕВА ПРИ ЭЛЕКТРОЛИТНО-ПЛАЗМЕННОЙ ЗАКАЛКЕ НА ХАРАКТЕРИСТИКИ СТАЛИ 20ГЛ**

*В данной статье представлено комплексное исследование процесса электролитно-плазменной закалки (ЭПЗ), применяемого к конструкционной стали 20GL, материалу, часто используемому в автомобильной, транспортной и различных других отраслях промышленности. Акутальностью данного исследования является необходимость повышения эксплуатационных характеристик сталей, которые подвергаются высоким механическим нагрузкам, повышенным температурам и коррозионным средам. Экспериментальные данные показывают, что электролитно-плазменная обработка существенно повышает твердость стали 20ГЛ в среднем примерно до 600HV. Кроме того, увеличение продолжительности нагрева значительно способствует повышению твердости, играя решающую роль в повышении износостойкости под нагрузкой. Микроструктурный анализ подтверждает образование мелкозернистой мартенситной фазы, подчеркивая трансформацию и упрочнение стали. Кроме того, в исследовании подчеркивается, что химический состав стали 20ГЛ влияет на градиент твердости от поверхности внутрь и приводит к развитию более мелкозернистых особенностей в микроструктуре стали. В целом электролитно-плазменный процесс оказывается полезным не только для улучшения механических характеристик, но и для повышения надежности и срока службы критических компонентов. С промышленной точки зрения эта технология отличается своей адаптивностью и экономической эффективностью, что делает ее привлекательным решением для таких секторов, как автомобилестроение, строительство и энергетическая промышленность. Таким образом, электролитно-плазменное упрочнение становится перспективным методом, соответствующим современным инженерным требованиям, предлагая многообещающий путь для усовершенствованной оптимизации материалов.*

***Ключевые слова:*** *электролитно-плазменное упрочнение, сталь 20ГЛ, твердость, износостойкость, коррозионная стойкость стали.*

**Information about the authors**

**Bauyrzhan Rakhadilov** – PhD, Vice-rector on scientific work of Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan; e-mail: rakhadilovb@mail.ru.

**Erzhan Shayakhmetov** – Senior Lecturer of the Department of Technological Equipment, Shakarim University, Kazakhstan; e-mail: shaiakhmeterzh@mail.ru.

**Zhanel Bakyt** – junior researcher of Engineering Center “Strengthening Technologies and Coatings», Shakarim University, Kazakhstan; e-mail: bakytzhanel@gmail.com.

**Sergei Buresh** – master’s student of the MTO-301 group, Shakarim University, Kazakhstan; e-mail: buresh2002@mail.ru.

**Nazira Musataeva*** – student of the F-302 group, Shakarim University, Kazakhstan; e-mail: naziramusataeva51@gmail.com.

**Авторлар туралы ақпарат**

**Бауржан Рахадилов** – PhD, Сәрсен Аманжолов атындағы Шығыс Қазақстан университетінің ғылыми жұмыс жөніндегі проректоры, Өскемен, Қазақстан; e-mail: rakhadilovb@mail.ru.

**Ержан Шаяхметов –** Технологиялық жабдықтар кафедрасының аға оқытушысы, Шәкәрім университеті, Қазақстан; e-mail: shaiakhmeterzh@mail.ru.

**Жанель Бақыт** – Шәкәрім университеті «Беріктендіру технологиялары және қаптамалар» инжиниринг орталығының кіші ғылыми қызметкері, Қазақстан; e-mail: bakytzhanel@gmail.com.

**Сергей Буреш** – Шәкәрім университетінің МТО-301 тобының магистранты, Қазақстан; e-mail: buresh2002@mail.ru.

**Назира Мусатаева*** – Шәкәрім университетінің Ф-302 тобының студенті, Қазақстан; e-mail: naziramusataeva51@gmail.com.

**Информация об авторах**

**Бауржан Рахадилов** – PhD, Проректор по научной работе Восточно-Казахстанского университета им. С. Аманжолова, г. Усть-Каменогорск, Казахстан; e-mail: rakhadilovb@mail.ru.

**Ержан Шаяхметов** – старший преподаватель кафедры технологического оборудования, Шәкәрім университет, Казахстан; e-mail: shaiakhmeterzh@mail.ru.
**Жанель Бақыт** – младший научный сотрудник Инжинирингового центра «Упрочняющие технологии и покрытия», Шәкәрім университет, Казахстан; e-mail: bakytzhanel@gmail.com.
**Сергей Буреш** – магистрант группы МТО-301, Шәкәрім университет, Казахстан; e-mail: buresh2002@mail.ru.
**Назира Мусатаева*** – студентка группы Ф-302, Шәкәрім университет, Казахстан; e-mail: naziramusataeva51@gmail.com.

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**A. Ualikhanov*, A. Sabitova, A. Klivenko, B. Rakhadilov, N. Mukhamediyarov**
Shakarim University,
071412, Republic of Kazakhstan, Semey, 20 A Glinka Street
*e-mail: icetea3221337@gmail.com

## MODERN APPROACHES TO METAL RECOVERY: ACID LEACHING AND BIOLEACHING TECHNOLOGIES

***Abstract:*** *With each passing year, the volume of metallurgical waste continues to grow, posing serious environmental and economic challenges. However, metallurgical by-products such as slags and tailings contain numerous valuable metals that can be recovered and reintegrated into production cycles. In this context, hydrometallurgical and bioleaching technologies are gaining particular relevance. These methods enable the efficient extraction of valuable components from waste while simultaneously reducing its volume and minimizing the environmental burden. This article examines how modern techniques, such as acid leaching and bioleaching, can be utilized not only to recover metals but also to address waste disposal issues with minimal ecological impact. Special attention is given to practical examples and research developments that demonstrate the high efficiency and industrial applicability of these technologies. This study highlights the importance of waste recycling not only from an ecological perspective but also as a critical step toward building a more sustainable economy where every resource is used to its fullest potential.*
**Key words:** *metallurgical waste, hydrometallurgy, bioleaching, recycling, ecology.*

### Introduction

Metallurgical waste is becoming an increasingly serious problem for both the environment and the economy every year. Traditional methods of disposal often fail to cope with the growing volumes and specific characteristics of such waste, leading to its accumulation and, consequently, significant environmental pressures. However, this challenge can be turned into an opportunity: slags, beneficiation tailings, and spent catalysts contain numerous valuable metals – copper, zinc, cobalt, and rare earth elements. These are valuable resources that, with proper processing, can be returned to production. Hydrometallurgy and bioleaching are emerging as some of the most effective solutions to this issue. These technologies enable the extraction of metals from waste through chemical reactions or biological processes [6, 7]. For instance, methods such as acid leaching or the use of microorganisms have already proven their effectiveness in both laboratory research and practical applications. These approaches not only reduce the volume of waste but also significantly minimize environmental pollution [2, 3]. This study focuses on examining modern technologies for metallurgical waste processing [9, 4]. Central to the analysis are hydrometallurgical and bioleaching methods, their advantages, and their practical application prospects. Additionally, the study explores the environmental aspects of these technologies and their economic feasibility. Of particular interest are innovations such as acid regeneration, the use of microorganisms, and carbothermal reduction, which enable recycling tasks to be addressed with minimal environmental impact [2,4]. Illustrative examples and research findings emphasize that metallurgical waste recycling is not only a way to address environmental challenges but also an opportunity for economic benefit. The implementation of such methods opens up prospects for more efficient resource utilization, reducing dependence on