

STUDY OF THE ELECTRICAL RESISTIVITY OF CARBONACEOUS MATERIALS**Zhakan A.***Zh. Abishev Chemical-Metallurgical Institute, Karaganda, Kazakhstan***Corresponding author e-mail: armat.medetuly@gmail.com***Author information:****Zhakan Armat**, Junior Researcher, Zh. Abishev Chemical-Metallurgical Institute, Karaganda, Kazakhstan, e-mail: armat.medetuly@gmail.com

Abstract — This paper presents the results of an investigation of the electrical resistivity of coals from the Borly and Saryadyr deposits over the temperature range of 200-1600 °C. The experimental study was carried out using a high-temperature laboratory Tammann furnace and a method for determining the electrical resistance of materials during heating. It was established that the electrical resistivity of both investigated coals decreases systematically with increasing temperature, indicating an increase in their electrical conductivity. Characteristic temperature regions associated with moisture removal, volatile matter release, and structural transformations of the carbonaceous phase were identified. The Borly coal was found to exhibit lower electrical resistivity than the Saryadyr coal over most of the investigated temperature range. At elevated temperatures, the difference between the samples gradually decreases. The obtained results are of practical importance for the selection of carbonaceous reducing agents and the assessment of the electrical characteristics of furnace charge materials during ferroalloy production in electric ore-thermal furnaces.

Keywords — electrical resistivity, coal, electrical conductivity, temperature, carbonaceous reducing agent, electric ore-thermal furnace, ferroalloys.

**КӨМІРТЕКТІ МАТЕРИАЛДАРДЫҢ МЕНШІКТІ ЭЛЕКТРЛІК КЕДЕРГІСІН
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Аңдатпа — Мақалада 200-1600 °C температура аралығында Борлы және Сарыадыр кен орындарының көмірлерінің меншікті электрлік кедергісін зерттеу нәтижелері келтірілген. Эксперименттік зерттеулер жоғары температуралы зертханалық Тамман пеші негізінде жасалған қондырғыда материалдардың қыздыру кезіндегі электрлік кедергісін анықтау әдісі арқылы жүргізілді. Температураның жоғарылауымен зерттелген екі көмірдің де меншікті электрлік кедергісінің заңды түрде төмендейтіні анықталды, бұл олардың электрөткізгіштігінің жоғарылағанын көрсетеді. Ылғалдың жойылуына, ұшқыш компоненттердің бөлінуіне және көміртекті фазаның құрылымдық өзгерістеріне байланысты электрлік кедергінің өзгеруінің негізгі температуралық аймақтары анықталды. Зерттелген температура диапазонының басым бөлігінде Борлы көмірінің меншікті электрлік кедергісі Сарыадыр көміріне қарағанда төмен екені анықталды. Жоғары температураларда зерттелген үлгілер арасындағы айырмашылық азаяды. Алынған нәтижелер ферроқорытпаларды кенді-термиялық пештерде балқыту кезінде көміртекті тотықсыздандырғыштарды таңдауға және шикіқұрамның электрлік сипаттамаларын бағалауға практикалық негіз болып табылады.

Түйін сөздер — меншікті электрлік кедергі, көмір, электрөткізгіштік, температура, көміртекті тотықсыздандырғыш, кенді-термиялық пеш, ферроқорытпалар.

ИССЛЕДОВАНИЕ УДЕЛЬНОГО ЭЛЕКТРИЧЕСКОГО СОПРОТИВЛЕНИЯ УГЛЕРОДСОДЕРЖАЩИХ МАТЕРИАЛОВ

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Аннотация — В статье представлены результаты исследования удельного электрического сопротивления углей месторождений Борлы и Сарыадыр в диапазоне температур 200-1600 °С. Экспериментальные исследования выполнены на установке на базе высокотемпературной лабораторной печи Таммана с использованием метода определения электрического сопротивления материалов при нагревании. Установлено, что с повышением температуры удельное электрическое сопротивление обоих исследуемых углей закономерно снижается, что свидетельствует об увеличении их электропроводности. Выделены характерные температурные области изменения электрического сопротивления, связанные с удалением влаги, выделением летучих компонентов и структурными преобразованиями углеродистой фазы. Показано, что уголь Борлы характеризуется более низким удельным электрическим сопротивлением по сравнению с углем Сарыадыр в большей части исследованного температурного диапазона. При высоких температурах различия между образцами уменьшаются. Полученные результаты имеют практическое значение для выбора углеродистых восстановителей и оценки электрических характеристик шихты при производстве ферросплавов в рудно-термических печах.

Ключевые слова — удельное электрическое сопротивление, уголь, электропроводность, температура, углеродистый восстановитель, рудно-термическая печь, ферросплавы.

KEY FINDINGS

The regularities of changes in the electrical resistivity of carbonaceous materials as a function of temperature were established. The effect of temperature on the electrophysical properties of the studied materials was demonstrated, and characteristic ranges of variation in their electrical resistivity were determined. The obtained results can be used to assess the electrical conductivity of carbonaceous materials under high-temperature conditions and to substantiate rational parameters for the electric-thermal processing of raw materials in ore-thermal furnaces.

INTRODUCTION

Analysis of the global raw material base for the metallurgical industry indicates a continuous depletion of high-quality mineral resources, while the requirements for the quality of metals and ferroalloys are becoming increasingly stringent. Under these conditions, the development of efficient technologies for processing complex and lower-grade raw materials requires a comprehensive understanding of their physicochemical properties. In particular, the electrical properties of raw materials play an important role in the operation of electric ore-thermal furnaces used for the production of ferroalloys and other metallurgical products.

The efficiency and applicability of ferroalloys are determined not only by their chemical composition, including the concentrations of the main elements and accompanying impurities, but also by a

range of physicochemical properties such as particle size distribution, density, surface characteristics, melting temperature, reducibility, and electrical conductivity. In industrial steelmaking practice, these properties significantly affect the behavior of charge materials during melting and, consequently, the efficiency of alloying and the overall performance of the metallurgical process.

The value of mineral raw materials is determined by a combination of economic and metallurgical characteristics. The economic value is associated with the costs of extraction and preliminary preparation of the raw material, including crushing, classification, and beneficiation. The metallurgical value is determined by the content of the main valuable elements, the amount and composition of gangue, the resulting slag composition and volume, the presence of harmful impurities such as phosphorus and sulfur, the amenability of the material to beneficiation, as well as its physical and physicochemical characteristics. Among the latter, strength, particle size distribution, porosity, moisture capacity, reducibility, melting temperature, and electrical resistivity are of particular importance for electric furnace processes.

The electrical resistivity of charge materials has considerable practical importance in the production of ferroalloys in electric ore-thermal furnaces. Changes in the electrical resistivity of the charge located in the furnace are directly associated with changes in the operating voltage, which is one of the principal electrical parameters of the furnace. The

furnace power, electrical and thermal losses, power factor ($\cos \phi$), and, consequently, the specific electrical energy consumption, which is one of the key technical and economic indicators of the process, depend on the operating voltage and the electrical characteristics of the charge.

Numerous studies have been devoted to the electrical resistivity of individual charge components used in electric ore-thermal furnaces. During the development of high-power electric furnaces for ferroalloy production, particular attention was paid to the electrical resistivity of individual concentrates and complex charge materials used for the smelting of various ferroalloys [1-6]. The electrical resistivity of manganese minerals [1,2,7], manganese concentrates, and charge mixtures for the production of manganese alloys [4-6] has been investigated. S. Morgulev [8] studied the electrical resistivity of carbonaceous reducing agents. S.I. Khitrik and Ya.F. Tsybakin [9] investigated the electrical resistivity of charge mixtures and individual charge components used in ferrosilicon production. A.S. Mikulinsky and L.V. Yumanova [10], as well as R.A. Chuguryan [11], studied the electrical conductivity of charge materials and their individual components used in calcium carbide production. M. Dermel and V. Marinchek [12] investigated the electrical conductivity of raw materials used in electric blast-furnace smelting.

Despite the considerable amount of research devoted to the electrical properties of metallurgical charge materials, the electrical resistivity of individual carbonaceous materials can vary significantly depending on their geological origin, petrographic composition, ash content, moisture content, porosity, degree of metamorphism, and temperature. Therefore, obtaining experimental data on the electrical resistivity of specific coal grades is important for assessing their suitability as carbonaceous reducing agents in electric ore-thermal processes.

In this regard, the study of the electrical resistivity of coals from the Saryadyr and Borly deposits is of practical and scientific interest. Determination of the temperature dependence of their electrical resistivity makes it possible to establish their electrical behavior under conditions relevant to high-temperature furnace processes and to assess the influence of the charge electrical characteristics on the energy parameters of electric ore-thermal furnaces.

Research Objective. The objective of this study is to investigate the electrical resistivity of coals from the Saryadyr and Borly deposits as a function of temperature and to determine the characteristic features of their electrical behavior under conditions relevant to electric ore-thermal processes.

Research Tasks. To achieve the stated objective, the following tasks were formulated:

1. To determine the electrical resistivity of the studied coals over the investigated temperature range and establish its temperature dependence.
2. To compare the electrical behavior of the Saryadyr and Borly coals and identify the characteristic temperature ranges of changes in their electrical resistivity.
3. To assess the practical significance of the obtained electrical characteristics for the use of these coals as carbonaceous reducing agents in electric ore-thermal furnace processes.

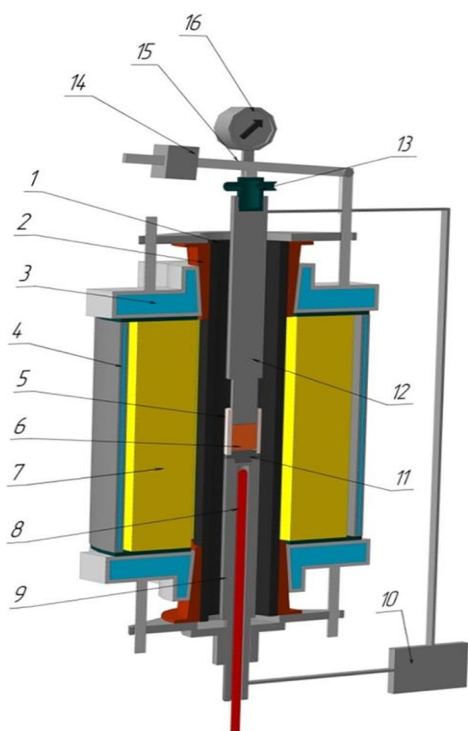
Scientific Novelty. The scientific novelty of the study consists in establishing the temperature dependence of the electrical resistivity of coals from the Saryadyr and Borly deposits and in identifying the characteristic features of their electrical behavior under heating conditions. The obtained experimental data provide a basis for comparative assessment of the electrical properties of the studied coals and can be used to improve the selection and proportioning of carbonaceous reducing agents in electric ore-thermal furnace charge materials.

MATERIALS AND METHODS

The experimental study employed the method proposed by V. I. Zhuchkov, which enables the determination of the electrical resistivity of materials at high temperatures while simultaneously recording the degree of their softening (shrinkage) [2].

For measurements of electrical resistivity during heating, the particle size of the initial material was maintained at 3-5 mm. The measurements were carried out in a Tammann high-temperature laboratory furnace. The electrical conductivity of the charge materials was investigated over a temperature range of 25-1600 °C at a heating rate of 15 °C/min. According to the Agroskin-Shumilov method, electrical resistance measurements were performed at 50 °C intervals. To increase the information content of the experimental data, automatic recording of electrical resistance values in the computer memory at 30-second intervals was implemented.

For this purpose, a special circuit was developed for connecting the measuring transducers to the Tammann laboratory furnace (Figure 1).



- 1 – carbon-graphite tube; 2 – copper clamping ring;
 3 – water-cooled cover; 4 – water-cooled housing;
 5 – alundum tube; 6 – investigated charge material;
 7 – protective lining; 8 – thermocouple; 9 – lower
 electrode; 10 – digital ohmmeter; 11 – graphite base
 for the alundum tube; 12 – upper electrode;
 13 – water cooling; 14 – load; 15 – lever;
 16 – electronic device for measuring shrinkage.

Figure 1 – Experimental setup for determining electrical resistivity and shrinkage (cross-sectional view).

The experimental setup consisted of a Tammann furnace in which the investigated material was heated. A sample with a height of 4 cm was placed in a cavity of an alundum crucible (5) with an internal diameter of 3 cm installed inside the furnace.

Data acquisition was performed using transducers connected to a thermocouple (8), electrodes (9, 12), and a device for measuring sample shrinkage. Graphite electrodes (9, 12), one of which was equipped with a hole for the thermocouple (8), were positioned on opposite sides of the sample to apply an electrical voltage across the material. The lower electrode was fixed in position, whereas the upper electrode was allowed to move downward as the material contracted under heating. A load (14) continuously pressed the upper electrode against the sample, ensuring reliable electrical contact. The pressure applied to the material was maintained at 0.02-0.04 MPa. The thermocouple was positioned through the lower electrode and electrically insulated from the alundum tube.

RESULTS AND DISCUSSION

A.A. Agroskin and S.N. Lyandyros investigated changes in the electrical resistivity of coal during cooling after preliminary heating. The studies showed that, when coal heated to 400 °C is subsequently cooled, its electrical resistivity returns to its initial value. For coal heated to 600 °C, the value of $\lg \rho$ at room temperature decreases by approximately two times compared with the initial value and corresponds to the electrical resistivity of coal at 400 °C. The electrical resistivity of coal heated to 800 °C partially recovers during cooling, whereas for coal heated to 1000 °C, the electrical resistivity remains practically unchanged [13].

The electrical resistivity of coal depends on its degree of metamorphism. Coals at an intermediate stage of metamorphism exhibit the highest electrical resistivity. Coals at a lower stage of metamorphism are characterized by somewhat higher electrical conductivity, whereas materials at an advanced stage of carbonization exhibit the lowest electrical resistivity [13].

The amount of mineral impurities also affects the electrical resistivity. With increasing ash content, the electrical resistivity of low- and medium-rank coals at room temperature decreases, whereas at elevated temperatures it increases. This phenomenon can be explained by the fact that, in low-rank coals, the electrical resistivity of the organic matter is considerably higher than that of the mineral impurities. Upon heating, the electrical resistivity of all coals increases with increasing ash content [13].

The electrical resistivity of a bulk layer of carbonaceous material consists of the intrinsic resistivity of the material and the resistance of transitional contacts between individual reducing-agent particles. The electrical resistivity of the charge increases with decreasing particle size of the carbonaceous reducing agent. The bath of a ferroalloy furnace acts as a bulk electrical conductor, and the distribution of current and power within it depends primarily on the electrical resistivity of the charge, which, in turn, is determined largely by the electrical conductivity of the reducing agent.

A high electrical resistivity of the charge makes it possible to increase the operating voltage and, consequently, the furnace power. At a given furnace power, an increase in the conductive-current component of the charge reduces the arc-current component. High electrical conductivity in the upper part of the furnace bath can lead to heating and sintering of the upper charge layer (the so-called “hot shock”) and to insufficient electrode penetration. In contrast, the use of a carbonaceous reducing agent with high electrical resistivity promotes deeper and more stable electrode penetration, reduces the conductive-current component of the charge, and contributes to

greater heat concentration in the lower zones of the furnace bath [13].

Figure 2 shows the dependence of the electrical resistivity of the Borly and Saryadyr coals on temperature.

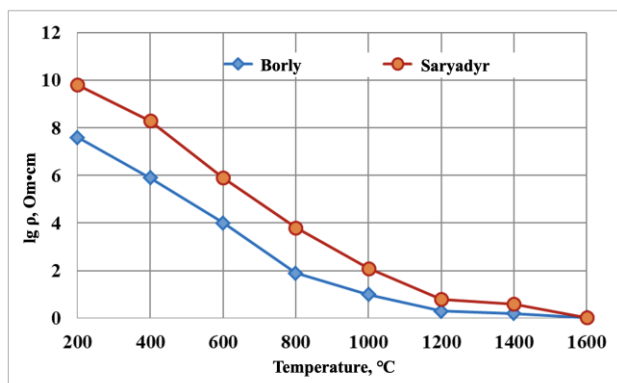


Figure 2 – Electrical Resistivity of Coals as a Function of Temperature

Figure 2 presents the temperature dependence of the electrical resistivity of the Borly and Saryadyr coals. The obtained curves demonstrate a pronounced decrease in electrical resistivity with increasing temperature, indicating a significant increase in the electrical conductivity of both carbonaceous materials. Based on the character of the curves, three characteristic temperature regions can be distinguished. The first region extends from 200 to 400 °C and is characterized by a relatively moderate decrease in electrical resistivity. The second region covers 400–1000 °C, where a more pronounced decrease in resistivity is observed. The third region corresponds to 1200–1600 °C and is characterized by very low resistivity values and a gradual approach of the curves toward similar values.

The change in electrical resistivity in the 200–400 °C range can be associated primarily with the removal of physically bound moisture and the initial thermal transformation of the organic matter. At the initial stage of heating, moisture evaporation and changes in the contact conditions between individual particles affect the electrical transport through the sample. As the temperature increases, the contribution of moisture to electrical conduction decreases, while the influence of the carbonaceous phase becomes increasingly dominant.

In the 400–1000 °C range, the electrical resistivity continues to decrease as a result of progressive thermal decomposition of the organic structure and the release of volatile components. These processes are accompanied by carbonization and structural rearrangement of the carbonaceous phase, which promote the formation of more electrically conductive pathways within the material. A particularly

pronounced decrease in electrical resistivity is observed at approximately 800 °C [14], which may indicate intensive structural transformations and an increase in the degree of carbonization of the coal.

At temperatures above 1000 °C, the resistivity of both samples decreases to very low values. In the 1200–1600 °C range, the difference between the Borly and Saryadyr coals becomes considerably smaller, and at 1600 °C their electrical resistivity approaches nearly the same value. This behavior indicates that at high temperatures the electrical properties of the samples are increasingly controlled by the thermally transformed carbonaceous phase rather than by their initial structural and compositional differences.

Throughout most of the investigated temperature range, the Saryadyr coal exhibits higher electrical resistivity than the Borly coal. At 200 °C, the values of $\lg \rho$ are approximately 9.8 and 7.6 Ohm·cm for the Saryadyr and Borly coals, respectively. At 800 °C, these values decrease to approximately 3.8 and 1.9 Ohm·cm, respectively. Thus, the Borly coal demonstrates higher electrical conductivity over a substantial part of the investigated temperature range. The observed difference may be related to variations in the petrographic composition, ash content, volatile matter content, degree of metamorphism, and structural characteristics of the two coals.

The pronounced decrease in electrical resistivity with increasing temperature is of practical importance for the application of these materials as carbonaceous reducing agents in electric ore-thermal furnaces. A decrease in charge resistivity leads to an increase in the conductive component of the electric current and can affect the distribution of electrical power and heat within the furnace bath. Therefore, the experimentally determined temperature dependence of electrical resistivity should be considered when selecting carbonaceous reducing agents and designing the electrical operating conditions of ferroalloy furnaces.

CONCLUSIONS

The electrical resistivity of the Borly and Saryadyr coals was investigated over the temperature range of 200–1600 °C. The results demonstrated a pronounced decrease in electrical resistivity with increasing temperature for both materials, indicating a significant increase in their electrical conductivity under heating.

The temperature dependence of electrical resistivity can be divided into three characteristic regions. The first region (200–400 °C) is associated mainly with moisture removal and initial thermal transformations of the coal structure. The second region (400–1000 °C) is characterized by a more pronounced decrease in resistivity, which can be attributed to the release of volatile matter and progressive carbonization. A particularly significant

decrease in electrical resistivity was observed at approximately 800 °C. At temperatures above 1000 °C, the resistivity decreased to very low values, and at 1600 °C the electrical properties of the two coals became close to each other.

Throughout most of the investigated temperature range, the Borly coal exhibited lower electrical resistivity than the Saryadyr coal. Consequently, Borly coal is characterized by higher electrical conductivity, whereas Saryadyr coal possesses comparatively higher electrical resistivity. The observed difference may be related to variations in the composition, ash content, degree of metamorphism, volatile matter content, and structural characteristics of the coals.

From the perspective of electric ore-thermal furnace operation, the obtained results indicate that the two coals may have different technological effects on the electrical characteristics of the furnace charge. The higher electrical resistivity of Saryadyr coal may be advantageous for increasing the operating voltage, reducing the conductive component of the current, and promoting deeper and more stable electrode penetration. In contrast, the higher electrical conductivity of Borly coal may contribute to a greater conductive-current component within the charge.

Therefore, Saryadyr coal can be considered more promising when a carbonaceous reducing agent with relatively high electrical resistivity is required for stable operation of an electric ore-thermal furnace, while Borly coal may be preferable in applications

where higher electrical conductivity of the charge is required. However, the final selection of a reducing agent should also take into account its chemical composition, fixed carbon content, ash content, volatile matter, reactivity, particle-size distribution, and mechanical properties.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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