



UDC 621. 793.79

DOI 10.17073/0368-0797-2026-3-258-264



Original article

Оригинальная статья

## METALLOGRAPHIC STUDIES OF THE ALLOY OF Co – Cr – Fe – Mn – Ni SYSTEM

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**Abstract.** In conditions of the Scientific and Production Center “Welding Processes and Technologies” of the Siberian State Industrial University, the developed flux-cored wires of the Co–Cr–Fe–Mn–Ni system were surfaced by automatic arc welding under a layer of flux. Chemical composition of the deposited coating samples was determined using the atomic emission method on the DFS-1 spectrometer and the X-ray fluorescence method on the XRF-1800 spectrometer. The research results indicate the possibility of obtaining coatings consisting of 60 – 70 % iron and 30 – 40 % alloying elements. Microstructural studies of the samples were carried out using the metallographic microscope METAM RV-34 and the NEXSYS ImageExpert software package. The deposited samples contain point oxides of grade 2a, non-deformable silicates of grade 4a, b. Compared with the substrate (09G2S steel), the resulting deposited layers of the samples are noticeably cleaner, however, K4 sample has less contamination. Microstructure of the first deposited layers is represented by needle-like martensite, which is confirmed by the results of microhardness measuring. Subsequent layers of the deposited samples are represented by an austenitic crystal structure. Moreover, the structure has an elongated (dendritic) structure, which is inherent in structures obtained by arc welding. The authors studied the microhardness distribution using the HVS-1000 microhardness tester according to Micro-Vickers GOST 9450 – 76. The results indicate the production of an alloy with a hardness slightly higher than that of the substrate used, while it is worth noting that the deposited layer contains zones with twice hardness. Most often, an increase in hardness is observed on the first deposited layers.

**Keywords:** flux-cored wire, electric arc surfacing, non-metallic inclusions, microstructure, microhardness, chemical composition

**Acknowledgements:** The work was supported by the Russian Science Foundation, grant No. 23-29-00350, <https://rscf.ru/project/23-29-00350/>.

**For citation:** Kryukov R.E., Konovalov S.V., Mikhno A.R., Panchenko I.A. Metallographic studies of the alloy of Co–Cr–Fe–Mn–Ni system. *Izvestiya. Ferrous Metallurgy*. 2026;69(3):258–264. <https://doi.org/10.17073/0368-0797-2026-3-258-264>

## МЕТАЛЛОГРАФИЧЕСКИЕ ИССЛЕДОВАНИЯ СПЛАВА СИСТЕМЫ Co – Cr – Fe – Mn – Ni

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**Аннотация.** В условиях НПЦ «Сварочные процессы и технологии» Сибирского государственного индустриального университета проведена наплавка разработанных порошковых проволок системы Co–Cr–Fe–Mn–Ni методом автоматической дуговой сварки под слоем флюса. Атомно-эмиссионным методом на спектрометре ДФС-1 и рентгенофлуоресцентным методом на спектрометре XRF-1800 определен химический состав образцов наплавленных покрытий. Результаты исследований указывают на возможность получения покрытий, состоящих из 60 – 70 % железа и 30 – 40 % легирующих элементов. С использованием металлографического микроскопа METAM RV-34 и программного комплекса NEXSYS ImageExpert проведены микроструктурные исследования образцов. В наплавленных образцах встречаются оксиды точечные балла 2а, силикаты недеформирующиеся балла 4а и 4б. По сравнению с подложкой (сталью 09Г2С) полученные наплавленные слои образцов заметно чище, однако образец К4 имеет меньшую загрязненность. Микроструктура первых наплавленных слоев представлена игольчатым мартенситом, что подтверждается результатами измерения микротвердости. Последующие слои наплавленных образцов представлены аустенитной кристаллической структурой. Причем структура имеет вытянутое (дендритное) строение, что присуще структурам, полученным методом дуговой наплавки. С помощью микротвердомера HVS-1000 по Микро-Виккерсу ГОСТ 9450 – 76 проведены исследования распределения микротвердости. Результаты указывают на получение сплава с твердостью, немного выше чем у используемой подложки, при этом стоит отметить, что в наплавленном слое присутствуют зоны с повышенной в два раза твердостью. Чаще всего повышение твердости наблюдается на первых наплавленных слоях.

**Ключевые слова:** порошковая проволока, электродуговая наплавка, неметаллические включения, микроструктура, микротвердость, химический состав

**Благодарности:** Исследование выполнено за счет гранта Российского научного фонда № 23-29-00350, <https://rscf.ru/project/23-29-00350/>.

**Для цитирования:** Крюков Р.Е., Коновалов С.В., Михно А.Р., Панченко И.А. Металлографические исследования сплава системы Co–Cr–Fe–Mn–Ni. *Известия вузов. Черная металлургия*. 2026;69(3):258–264. <https://doi.org/10.17073/0368-0797-2026-3-258-264>

## INTRODUCTION

For more than half a century since the first flux-cored wire was developed, welding and surfacing technologies using high-alloy welding consumables have been applied to metallic components [1–3]. The most widely used surfacing consumables are Fe–C-based flux-cored wires additionally containing various refractory elements, such as chromium, tungsten, molybdenum, titanium, and boron [4–6]. The use of these materials for surfacing can substantially improve the service properties and reliability of components, including strength, hardness, ductility, and wear resistance [7; 8], while also reducing manufacturing costs through the use of secondary raw materials in the flux-cored wire charge [9; 10].

Under the high-energy action of an electric arc, whose column temperature may reach 6200 K, the metal of the permanent joint formed by the substrate (the worn surface being restored) and the arc-deposited coating undergoes a complex set of interrelated physical, physico-chemical, and thermophysical phenomena and processes. These processes involve changes in the state of matter, micro- and macrostructure, dislocation substructure, and chemical and phase compositions of the substrate and coating, thereby determining the resulting set of properties [11–13].

Alloying additions to the flux-cored wire charge can modify the chemical composition of the deposited coating and, consequently, the mechanical properties of the component [14; 15].

For example, molybdenum steels used in combination with several other alloying materials promote the formation of a high-hardness coating suitable for high-speed cutting tools [16; 17].

Chromium steels containing more than 12 % Cr are corrosion- and heat-resistant at temperatures up to 600 °C. Depending on their carbon-to-chromium ratio, these steels may have ferritic, martensitic, or ferritic-martensitic structures. Chromium steels are used to surface components for various applications, including hydraulic press plungers, rolling-mill rolls, dies, and start-up and control valves [18; 19].

Austenitic steels are used for different applications depending on their alloying-element content. Metastable austenitic steels are used to surface components subjected

to severe impact and dynamic loading, which induces austenite transformation and increases hardness [20–22].

The aim of this study was to fabricate and perform metallographic characterization of a metal layer deposited using a Co–Cr–Fe–Mn–Ni system flux-cored wire.

## MATERIALS AND METHODS

Charge component quantities for the developed flux-cored wire were calculated according to the procedure described in [23]. The wire was fabricated using the following powdered metallic materials: PKh-1S chromium powder (TU 14-1-1474-75), MR-0 manganese powder (GOST 6008-82), PK-1u cobalt powder (GOST 9721-79), and PNK 1L5 nickel powder (GOST 9722-97). The wire sheath was made from a 0.5-mm-thick, 15-mm-wide AISI 304 stainless steel strip. The flux-cored wire was produced on a laboratory unit at the Scientific and Production Center “Welding Processes and Technologies” of the Siberian State Industrial University (SibSIU). The manufactured wire had a diameter of 4 mm.

Four to five passes were deposited on a structural low-alloy 09G2S steel substrate using an AOTAI ASAW-1250 welding tractor and AN-348A welding flux. The following previously optimized surfacing mode was used: current, 420 A; voltage, 38 V; and travel speed, 15 cm/min.

Samples were prepared for examination using a REALREZ M51 band saw and a MODUL MP-1000 grinding and polishing machine.

The chemical composition of the deposited coatings was determined using the equipment of the Materials Science Shared Research Center of SibSIU by the atomic emission method on a DFS-71 spectrometer and by the X-ray fluorescence method on an XRF-1800 spectrometer.

Metallographic examinations were performed using a METAM RV-34 metallographic microscope and NEXSYS ImageExpert software. Non-metallic inclusions in the deposited layers were evaluated in accordance with GOST 1778-2022 at 100× magnification. The microstructure was examined at 100×, 400×, and 1000× magnification.

Microhardness was measured using an HVS-1000 tester by the Micro-Vickers method (GOST 9450-76) with a diamond pyramidal indenter. The test load was 9.8 N, and the dwell time was 10 s.

**Table 1. Compositions of flux-cored wire charge**

**Таблица 1. Составы шихты порошковой проволоки**

| Sample ID | Flux-cored wire charge components, g |                     |                   |                     |
|-----------|--------------------------------------|---------------------|-------------------|---------------------|
|           | PKh-1S<br>(Chromium)                 | MR-0<br>(Manganese) | PK-1u<br>(Cobalt) | PNK 1L5<br>(Nickel) |
| K3        | 10                                   | 35                  | 40                | 15                  |
| K4        | 10                                   | 40                  | 35                | 15                  |

## RESULTS AND DISCUSSION

Samples differing in the concentration of alloying elements in the powder wire were manufactured by multi-pass surfacing (Fig. 1; Table 1).

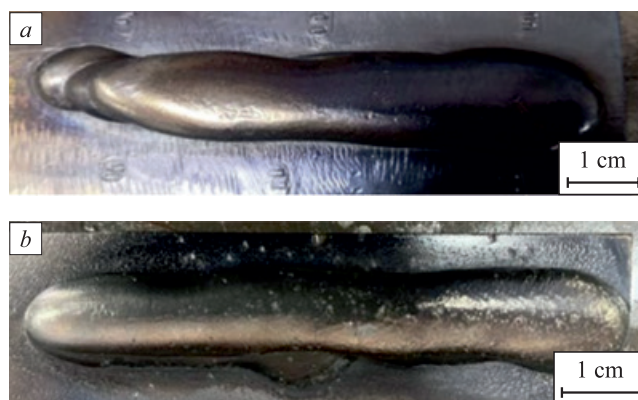
The chemical analysis results for the deposited layer are presented in Table 2. The deposited metal contained 60 – 70 % Fe and 30 – 40 % alloying elements.

The non-metallic inclusion content of the deposited layer (Fig. 2) was assessed on the end face of each sample. According to the GOST 1778-2022 reference charts, the deposited samples contained grade 2a point oxides and grade 4a and 4b non-deformable silicates. Sample K4 had a lower inclusion content than sample K3, however, the deposited layers of both samples were considerably cleaner than the 09G2S steel substrate.

Fig. 3 presents the arrangement of the microhardness measurement points.

The microhardness measurement results (Table 3) show that the layers deposited using Co – Cr – Fe – Mn – Ni

system flux-cored wires had slightly higher microhardness than the substrate. The deposited layer also contained regions with approximately twice the microhard-



**Fig. 1.** Characteristic appearance of deposited samples:  
*a* – sample K3; *b* – sample K4

**Рис. 1.** Характерный вид наплавленных образцов:  
*a* – образец K3; *b* – образец K4

**Table 2. Chemical composition of deposited samples**

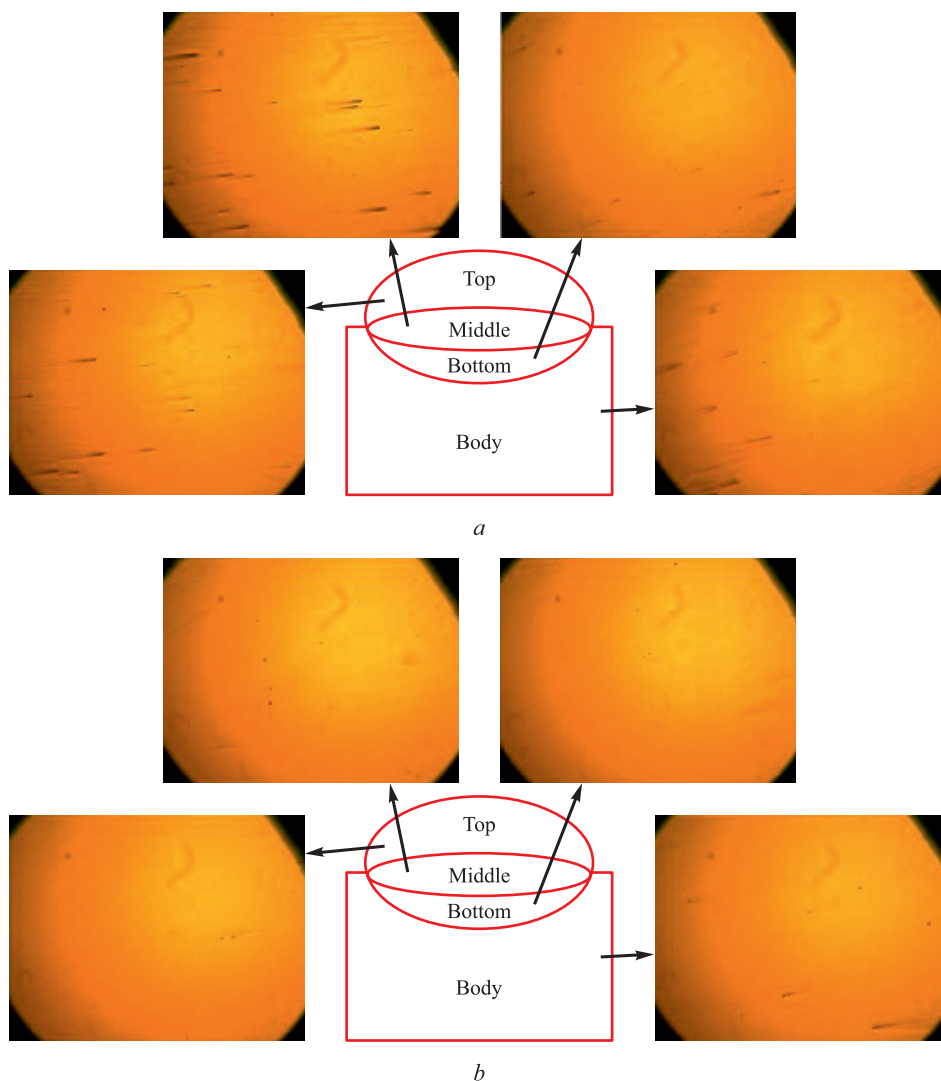
**Таблица 2. Химический состав наплавленных образцов**

| Sample ID | Element content, wt. % |      |       |       |      |       |       |       |      |       |       |      |         |
|-----------|------------------------|------|-------|-------|------|-------|-------|-------|------|-------|-------|------|---------|
|           | Si                     | Mn   | Cr    | Ni    | Cu   | W     | V     | Mo    | Al   | S     | P     | Co   | Fe      |
| K3        | 0.83                   | 4.80 | 17.88 | 9.47  | 0.03 | 0.048 | 0.078 | 0.017 | 0.24 | 0.008 | 0.038 | 5.98 | balance |
| K4        | 0.75                   | 5.73 | 17.06 | 11.39 | 0.03 | 0.110 | 0.072 | 0.019 | 0.18 | 0.012 | 0.035 | 5.44 | balance |

**Table 3. Results of measurement of microhardness (HV) of deposited samples**

**Таблица 3. Результаты измерения микротвердости (HV) наплавленных образцов**

| Sample ID | Microhardness at measurement point |     |     |     |     |     |     |     |                           |     |          |     |     |     |     |     |     |
|-----------|------------------------------------|-----|-----|-----|-----|-----|-----|-----|---------------------------|-----|----------|-----|-----|-----|-----|-----|-----|
|           | 1                                  | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9                         | 10  | 11       | 12  | 13  | 14  | 15  | 16  | 17  |
| K3        | 176                                | 161 | 149 | 155 | 175 | 182 | 164 | 161 | 150                       | 146 | 148      | 154 | 157 | 142 | 145 | 186 | 162 |
| K4        | 143                                | 138 | 139 | 140 | 132 | 132 | 144 | 139 | 137                       | 135 | 136      | 146 | 152 | 137 | 127 | 309 | 313 |
| Sample ID | Microhardness at measurement point |     |     |     |     |     |     |     |                           |     |          |     |     |     |     |     |     |
|           | 18                                 | 19  | 20  | 21  | 22  | 23  | 24  | 25  | Base metal<br>(substrate) |     | Mean, HV |     |     |     |     |     |     |
| K3        | 160                                | 149 | 155 | 126 | 167 | 147 | 220 | 126 | 120 – 130                 |     | 159      |     |     |     |     |     |     |
| K4        | 138                                | 124 | 123 | 125 | 127 | 129 | 131 | 192 |                           |     | 151      |     |     |     |     |     |     |



**Fig. 2.** Contamination of samples K3 (a) and K4 (b) with nonmetallic inclusions

**Рис. 2.** Загрязненность образцов K3 (a) и K4 (b) неметаллическими включениями

ness. These regions were most frequently observed in the first deposited layers.

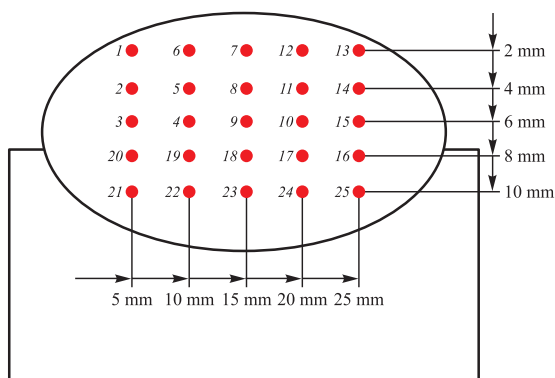
Microstructural analysis (Fig. 4) was performed after etching the deposited samples with aqua regia. The sub-

strate had a ferrite-pearlite structure. Needle-like martensite was observed in the first deposited layers, consistent with the microhardness measurement results. The subsequent layers of the deposited samples had an austenitic structure with elongated (dendritic) morphology characteristic of the samples produced by arc welding.

## CONCLUSIONS

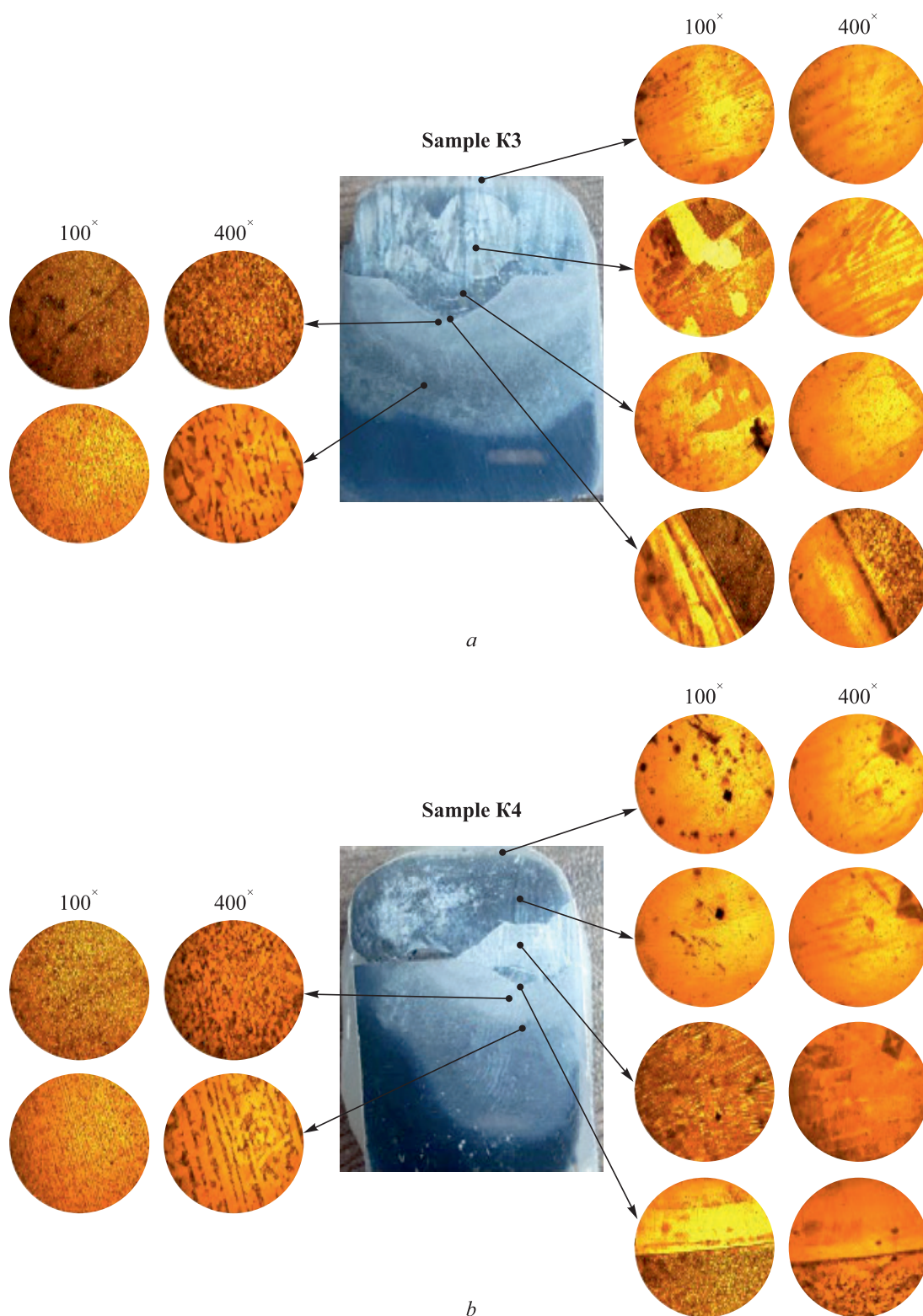
The study confirmed the feasibility of producing Co–Cr–Fe–Mn–Ni system coatings using flux-cored wires, with an Fe content of 60 – 70 % and a total alloying-element content of 30 – 40 %.

Evaluation of non-metallic inclusions showed that the deposited samples contained grade 2a point oxides and grade 4a and 4b non-deformable silicates. Sample K4 had a lower inclusion content than sample K3, while the deposited layers of both samples were substantially cleaner than the 09G2S steel substrate.



**Fig. 3.** Arrangement of microhardness measuring points

**Рис. 3.** Схема расположения точек измерения микротвердости



**Fig. 4.** Microstructure of samples K3 (a) and K4 (b)

**Рис. 4.** Микроструктура образцов K3 (a) и K4 (b)

The microhardness of the deposited metal was slightly higher than that of the substrate. Localized regions, predominantly in the first layers, exhibited approximately twice the microhardness; this was associated with the formation of needle-like martensite.

Microstructural analysis showed that the initial deposited layers contained needle-like martensite, whereas the subsequent layers had an austenitic crystal structure with elongated dendritic morphology characteristic of arc welding.

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Разработка технологии изготовления электродов и порошковых проволок для сварки и родственных процессов: учебно-методическое пособие / А.С. Табачников, Ю.С. Коробов, Н.М. Разиков, Л.А. Онищенко; под общ. ред. Ю.С. Коробова. Екатеринбург: Изд-во Урал. ун-та; 2023:112.

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Received 09.06.2025  
Revised 27.05.2026  
Accepted 01.04.2026

Поступила в редакцию 09.06.2025  
После доработки 27.03.2026  
Принята к публикации 01.04.2026