DOI: https://doi.org/10.37434/tpwj2025.07.03

WELDING AND TECHNOLOGICAL PROPERTIES OF SPARSELY ALLOYED FLUX-CORED WIRES FOR STRENGTHENING AND REPAIR OF PARTS BY ARC SURFACING

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ABSTRACT

The results of a comparative study of the welding and technological properties of the developed sparsely alloyed flux-cored wires (FCWs) of two types: PP-Np-50Kh2MNSGF and PP-Np-20KhGS are presented. The evaluation was performed using a comprehensive procedure that includes three components: visual inspection of the surfacing process, evaluation of melting characteristics, and determination of arc process stability. A digital self-recording ANENG AN9002 multimeter was used to monitor the surfacing parameters. As a reference, the standard FCW of PP-Np-25Kh5FMS grade, developed at the E.O. Paton Electric Welding Institute of the NAS of Ukraine (PWI), was used. The experimental comparative analysis demonstrated that surfacing with the developed FCWs is characterized by high process stability, good quality of the deposited metal formation, absence of macrodefects, and satisfactory slag crust separation. Microstructural analysis of the deposited layers confirmed the absence of microdefects (pores, cracks, lacks of fusion) and revealed a distinct fusion line between the base metal and the deposited metal. The results of the comprehensive comparative analysis of the developed sparsely alloyed FCWs demonstrated that they possess similar or improved welding and technological characteristics compared to the standard reference wire. This indicates the feasibility of using the developed FCWs for arc surfacing applications. Considering the purpose of the developed FCWs, they can be effectively used to enhance the wear resistance and service life of parts in special-purpose and industrial equipment, which is particularly relevant in the context of Ukraine's post-war reconstruction and strengthening of its defence capability.

KEYWORDS: arc surfacing, flux-cored wire, deposited metal, welding and technological properties, resource saving

INTRODUCTION

In the context of Ukraine's post-war reconstruction and ensuring its defence capability, it is crucial to introduce efficient and cost-effective technologies for repair and restoration of damaged parts of military equipment and industrial machinery. Flux-cored wire (FCW) arc surfacing is one of the most promising methods that allows restoring and strengthening the surfaces of various parts due to its wide capabilities of ensuring the required composition of the deposited metal at minimal material consumption [1–7].

FCW arc surfacing has a number of significant advantages [1–7]. Firstly, this method makes it possible to form wear-resistant coatings with the required hardness, strength and corrosion resistance, which significantly extends the service life of parts. Secondly, the technology ensures high efficiency, as it allows surfacing large volumes of metal in a short time with minimal material losses. Thirdly, FCWs make it possible to obtain a stable quality of the deposited metal due to the uniform distribution of alloying elements and the ability to adjust their composition.

However, the available FCWs are often imported and/or not adapted to the specific operating conditions of special and industrial machinery parts used in Ukraine. In addition, when solving the problem of restoring a specific part, it is necessary to take into account its operating conditions, chemical composition of the material, and required properties, and, therefore, it is often necessary to develop a new FCW that will ensure the achievement of the set tasks.

The use of FCW with an optimized composition ensures effective alloying of the deposited metal, allowing the reduction in the content of scarce alloying elements without losses in mechanical properties [8–12]. This is especially important in the context of the need in shortening the raw material costs. The introduction of sparsely alloyed FCWs will promote the creation of resource-saving technologies, reduce dependence on imported materials and increase the technological autonomy of the defence and repair industries. Thus, the development of sparsely alloyed FCWs for arc surfacing is an urgent task due to the need in improving the efficiency of repair and restoration of parts, especially in the context of Ukraine's post-war reconstruction and ensuring its defence capability.

The main task in developing new FCWs is to determine their welding and technological properties, which directly affect the stability of the surfacing process, quality and service life of restored parts. Determining the optimal surfacing modes to improve the process stability and efficiency, reduction in the tendency to defect formation, and ensuring high quality of deposited metal formation are crucial in providing the reliability and efficiency of restoration of machine and machinery parts.

THE AIM

of the study is to determine and comparatively analyze the welding and technological characteristics of the developed sparsely alloyed FCWs for arc surfacing with the standard FCW reference to evaluate the possibility of using the developed experimental FCWs in strengthening and restoration of various parts for the needs of the defence industry and Ukraine's post-war reconstruction.

MATERIALS AND RESEARCH PROCEDURES

Parameters related to welding and technological properties depend on the object of study. Therefore, researchers choose or develop procedure for their determination in each specific case, depending on the set tasks. Based on the above, the evaluation of welding and technological properties was performed according to the developed comprehensive experimental procedure, which consists of three components [13].

The first component includes a visual expert evaluation of the arc surfacing process and the produced deposited metal. The controlled parameters included in the mentioned component are the arc excitation nature, the quality of the deposited metal formation, the presence of visible defects and the quality of slag crust separation (provided that submerged arc surfacing or surfacing using self-shielded FCW is applied).

The second component includes the evaluation of the melting characteristics (efficiency) of FCW, which is determined by the melting, deposit and loss factors. The higher the melt and deposition indices and the lower the loss rate, the higher the FCW deposition efficiency.

The third component includes the evaluation of the arc surfacing process stability, which was performed based on the dispersion of the actual values of arc current and voltage during their repeated record by the calculated corresponding constants of variation. The use of the constant of variation as a controlled parameter makes it possible to eliminate the influence of the scale of different samples of the obtained data.

Figure 1. Appearance of the laboratory surfacing installation: *1* — welding automatic machine A-1406; *2* — control panel; *3* — welding table with a fixed test specimen; *4* — measuring shunt; *5* — digital self-recording ANENG AN9002 multimeter

To record the mode parameters during the surfacing process, a digital self-recording ANENG AN9002 multimeter equipped with a high-speed analogue-to-digital converter was used (Figure 1).

As the base metal, plates of St.3 steel, as well as plates of special 13Kh11N2V2MF and SWEBOR ARMOR 560 (35G2KhS) steels of 12 mm thick were used. Two types of experimental FCWs were studied in the work:

- No. 1 — PP-Np-50Kh2MNSGF microalloyed with boron (0.01 %), which provides a deposited metal with high wear and impact resistance and hardness of 55–59 *HRC*. It is applied for surfacing armour plates of parts operating under conditions of mechanical wear and local high-intensity impact loads;
- No. 2 — PP-Np-20KhGS, which provides a deposited metal of low-carbon low-alloy steel with a hardness of 30–35 *HRC*. It is applied for surfacing worn parts of the propulsion system of tracked special and military vehicles.

The standard FCW of the PP-Np-25Kh5FMS grade, manufactured in accordance with the technical specifications, developed at the PWI, was used as a reference [14]. The diameter of all used FCWs was 2.4 mm, and the filling factor was 25 %. The protective medium in surfacing was AN-26P flux. The sur-

Table 1. Comparative evaluation of welding and technological properties of FCW

No.	Type of deposited metal	Arc excitation nature	Quality of deposited metal formation	Presence of defects	Quality of slag crust separation	Total number of points	Factors, %				
							Melting	Surfacing	Losses	Current variation	Voltage variation
1	50Kh2MNSGF	2	1	2	1	6	16.2	15.1	6.8	15.2	7.6
2	20KhGS	2	1	2	2	7	15.3	14.4	5.4	14.7	6.2
3	25Kh5FMS	2	1	2	1	6	16.4	15.2	7.3	17.2	8.5

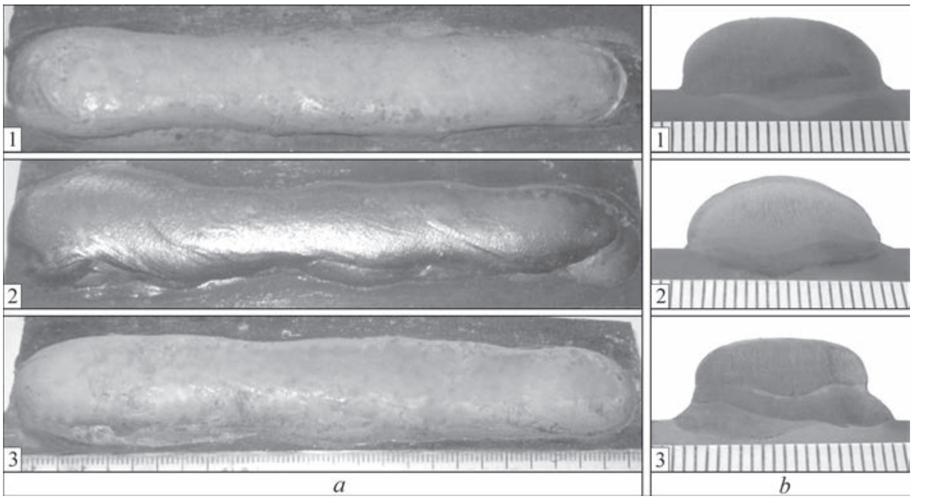

Figure 2. Appearance (*a*) and cross macrosections (*b*) of billets deposited using FCWs Nos 1–3. Wire designations are given in Table 1

facing conditions were chosen using the recommendations [4], which were the same for all specimens: voltage — 28 V, current — 300 A, deposition rate — 20 m/h.

RESEARCH RESULTS

Table 1 below summarizes the information on the evaluation of welding and technological properties. The appearance of the billets of St.3 after deposits on them performed using PP-Np-50Kh2MNSGF, PP-Np-20KhGS and PP-Np-25Kh5FMS wires, as well as their cross-sections are shown in Figure 2.

The quality of metal formation deposited on plates made of special 13Kh11N2V2MF and SWEBOR ARMOR 560 steels using PP-Np-50Kh2MNSGF wire is shown in Figure 3. Histograms of the distribution of current and voltage values on the arc, which were used to evaluate the stability of the surfacing process, are shown in Figure 4.

It was experimentally determined that the studied developed wires provide easy arc excitation, satisfactory quality of the deposited metal and the absence of defects in it (Figure 2), as well as satisfactory quality of slag crust separation.

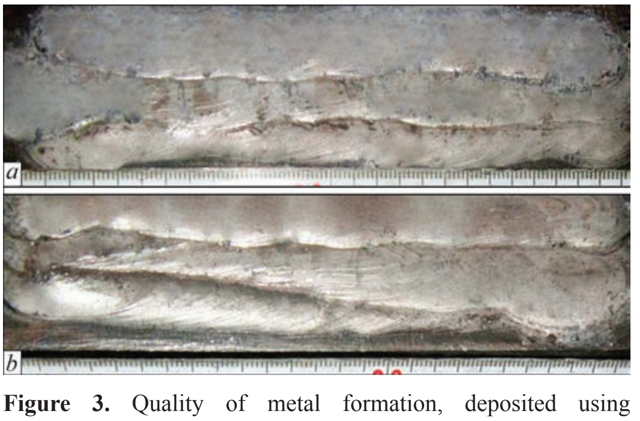

Figure 3. Quality of metal formation, deposited using PP-Np-50Kh2MNSGF wire on billets of 13Kh11N2V2MF (*a*) and SWEBOR ARMOR 560 (*b*) steel

An experimental evaluation of the possibility of using wire No. 1 (PP-Np-50Kh2MNSGF) as a material for surfacing wear-resistant layers on special steels of domestic (13Kh11N2V2MF) and imported (SWEBOR ARMOR 560) production showed the prospects of its use. According to the results of surfacing using the developed FCW on the plates of the abovementioned steels, good quality of multilayer metal formation and the absence of defects in the form of cracks, pores, lacks of fusion, etc. were noted (Figure 3).

Analyzing the obtained data (see Table 1, Figure 4), it was found that the experimental FCWs No. 1 and 2 have similar or better welding and technological characteristics compared to the reference FCW No. 3. Wire No. 1 demonstrates melting and deposit factors similar to the indices of the reference wire and exceeds the similar characteristics of wire No. 2. The loss factor is the lowest for wire No. 2, which indicates its greater efficiency in the use. Wire No. 1 has a lower loss factor than the reference wire, which also indicates its efficiency. The best surfacing stability is demonstrated by wire No. 2, which has the lowest constants of variation in current and voltage (14.7 and 6.2 %, respectively), while for wire No. 1 they amount to 15.2 and 7.6 %, which is also better compared to the reference (17.2 and 8.5 %, respectively).

The analysis of the microstructure of the specimens deposited using FCWs No. 1 and 2 showed (Figure 5) that in the specimens deposited using both types of wires, the fusion line of the deposited (top) and base (bottom) metal is quite distinct, and there are no internal microdefects in the form of pores, cracks, lacks of fusion, nonmetallic inclusions, etc.

Thus, the developed experimental FCWs No. 1 (PP-Np-50Kh2MNSGF) and No. 2 (PP-Np-20KhGS) have advantages over the reference wire or are not inferior to it in terms of the main welding and techno-

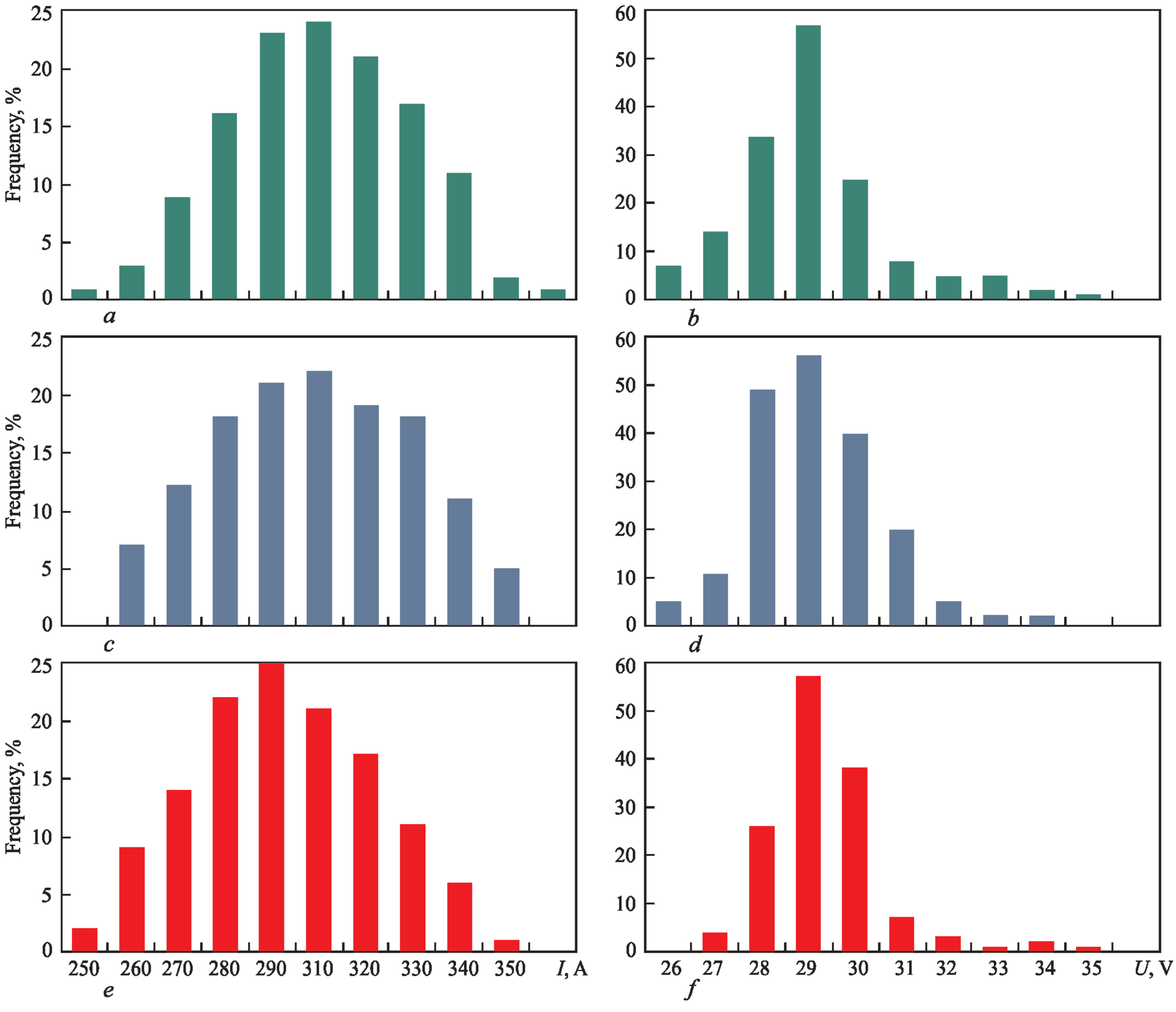

Figure 4. Histograms of current (*a*, *c*, *e*) and voltage (*b*, *d*, *f*) distribution during surfacing using FCWs: No. 1 (*a*, *b*), No. 2 (*c*, *d*) and No. 3 (*e*, *f*). Wire designations are shown in Table 1

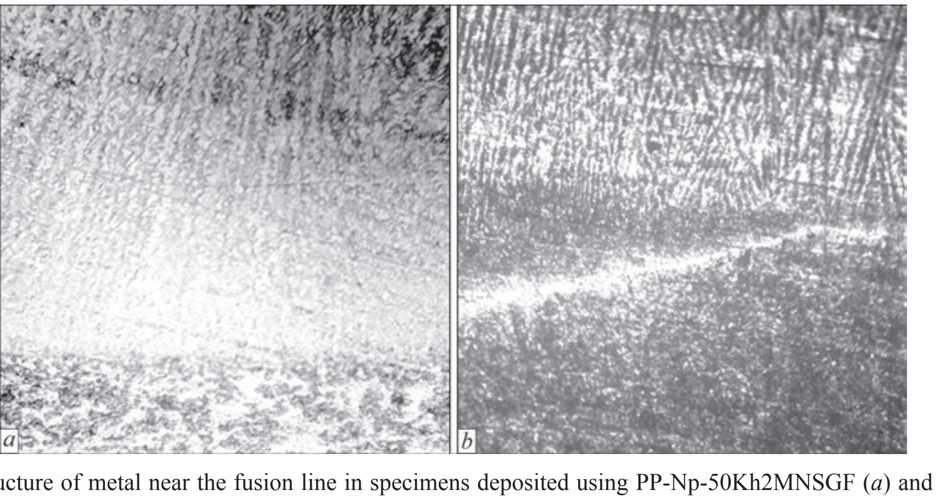

Figure 5. Microstructure of metal near the fusion line in specimens deposited using PP-Np-50Kh2MNSGF (*a*) and PP-Np-20KhGS (*b*) wires, ×240

logical characteristics, which confirms the possibility of their use for electric arc surfacing. The developed sparsely alloyed FCWs of two types, in accordance with their purpose, as described above, can be used in the manufacture or restoration of parts of special and industrial machinery to increase its service life.

CONCLUSIONS

1. According to the developed comprehensive procedure, a comparative analysis of the welding and technological characteristics of the developed sparsely alloyed flux-cored PP-Np-50Kh2MNSGF and PP-Np-20KhGS wires was carried out to deter-

mine the possibility of their wide practical application in electric arc surfacing of parts for various purposes.

2. As a result of the conducted comparative studies, it was found that the developed sparsely alloyed experimental flux-cored wires are not inferior, and in some aspects exceed the characteristics of the standard reference wire in terms of the main welding and technological parameters (ease of arc excitation, quality of deposited metal, factors of melting, deposit, losses and current/voltage constants of variation).

3. The obtained results confirm the feasibility of further development and implementation of experimental FCWs in repair and production processes for the needs of the defence industry and post-war restoration of infrastructure in Ukraine.

REFERENCES

1. Pokhodnya, I.K., Shlepakov, V.N., Maksimov, S.Yu., Ryabtsev, I.A. (2010) Research and developments of the E.O. Paton Electric Welding Institute in the field of electric arc welding and surfacing using flux-cored wire (Review). *The Paton Welding J.*, **12**, 26–33.
2. Kuskov, Yu.M. (2019) Application of flux-cored wires at surfacing, remelting and in metallurgy. *The Paton Welding J.*, **3**, 27–33. DOI: https://doi.org/10.15407/tpwj2019.03.05
3. Poznyakov, V.D., Gajvoronsky, A.A., Klapatyuk, A.V. et al. (2019) Flux-cored wire for restoration surfacing of worn surfaces of railway wheels. *The Paton Welding J.*, **7**, 36–40. DOI: https://doi.org/10.15407/tpwj2019.07.08
4. Babinets, A.A. (2023) Control of formation of metal produced by arc methods of layer-by-layer deposition of material with flux-cored wires. *The Paton Welding J.*, **11**, 35–40. DOI: https://doi.org/10.37434/tpwj2023.11.04
5. Kuskov, Yu.M., Zhdanov, V.A., Ryabtsev, I.O. et al. (2020) Methods for increasing the corrosion resistance of coatings deposited under a flux layer from high-chromium powder wires. *Mater Sci.*, **55**, 710–715. DOI: https://doi.org/10.1007/s11003-020-00362-9
6. Szymura, M., Czupryński, A., Ochodek, V. (2024) Development of a mathematical model of the self-shielded flux-cored arc surfacing process for the determination of deposition rate. *Materials*, 17(**22**), 5616. DOI: https://doi.org/10.3390/ma17225616
7. Shlepakov, V.N. (2014) Physical-metallurgical and welding-technological properties of gas-shielded flux-cored wires for welding of structural steels. *The Paton Welding J.*, **6–7**, 53–56. DOI: https://doi.org/10.15407/tpwj2014.06.10
8. Golovko, V., Kotelchuk, O., Naumeiko, S., Golyakevich, A.A. (2022) Development of self-shielded flux-cored wires for arc welding of low-alloy steels. *Defect and Diffusion Forum*, **416**, 103–114. DOI: https://doi.org/10.4028/p-58v9g5
9. Trembach, B.O., Silchenko, Yu.A., Sukov, M.G. et al. (2024) Development of a model of transition element factor of alloying elements of self-shielding flux-cored powder wire and optimization of its core filler composition. *Mater Sci.*, **59**, 733–740. DOI: https://doi.org/10.1007/s11003-024-00834-2
10. Stupnyts'kyi, T.R., Student, M.M., Pokhmurs'ka, H.V., Hvozdets'kyi, V.M. (2016) Optimization of the chromium content of powder wires of the Fe–Cr–C and Fe–Cr–B systems according to the corrosion resistance of electric-arc coatings. *Mater Sci.*, **52**, 165–172. DOI: https://doi.org/10.1007/s11003-016-9939-8
11. Zhang, T., Yang, K., Zhu, Z. et al. (2024) Effect of Cr and W on microstructure and wear resistance of arc additive manufactured flux-cored wire for railway wheels. *J. of Materials Research and Technology*, **30**, 3438–3447. DOI: https://doi.org/10.1016/j.jmrt.2024.04.088
12. Malinov, V.L. (2006) Sparsely alloyed consumables providing in the deposited metal deformation hardening in operation. *The Paton Welding J.*, **8**, 25–28.
13. Babinets, A.A., Ryabtsev, I.O., Lentyugov, I.P. (2025) Methodology for evaluating the welding and technological properties of flux-cored wires for arc surfacing. *Avtomatychne Zvaryuvannya*, **2**, 38–44 [in Ukrainian]. DOI: https://doi.org/10.37434/as2022.02.05
14. TUU 28.7.05416923.066–2002: *Flux-cored wires for surfacing*. Kyiv, PWI [in Russian].

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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SUGGESTED CITATION

S.Yu. Maksymov, A.A. Babinets, I.P. Lentyugov, V.V. Osin (2025) Welding and technological properties of sparsely alloyed flux-cored wires for strengthening and repair of parts by arc surfacing. *The Paton Welding J.*, **7**, 18–22.
DOI: https://doi.org/10.37434/tpwj2025.07.03

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Received: 13.02.2025
Received in revised form: 24.04.2025
Accepted: 02.07.2025