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Comparative Analysis of the Effects of Additives of Nanostructured Functional Ceramics on the Properties of Welding Electrodes

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Abstract: The synthesis of special photocatalysts of nanostructured functional ceramics (PNFC) under the ZKHM brand under the influence of concentrated solar radiation showed the effectiveness of these ceramic materials in multifunctional use, in particular as additives for coatings of welding electrodes. However, problems with producing these materials in solar ovens on an industrial scale did not allow the widespread use of this method. This problem was solved using the technique of PNFC synthesis, followed by activation by pulsed radiation generated by functional ceramics. The ceramic material obtained by this method under the brand name ZB-1 also showed its effectiveness when used as an additive in welding electrode coatings. A comparative analysis of the effectiveness of the actions of additives from the ZKHM and ZB-1 brands on the welding and technological properties of welding electrodes from the MR-3 brand was carried out. Comparative results for the formation of weld beads showed that beads with high-quality formation without external defects were achieved when surfaced with electrodes with additives from both brands at concentrations up to 1%. Also, at concentrations up to 1%, these additives increased the breaking length of the arc and the stability of arc welding. The different effects of these additives were observed in a comparative analysis of their impacts on the size of the visor at the end of the electrode, the coefficients of melting and surfacing, and the loss factor for fumes and splashing of electrode metal.

Keywords: shield metal arc welding; welding electrodes; nanostructured functional ceramics (NFCs)

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1. Introduction

Welding is the most common fabrication method for joining parts. Shield metal arc welding (SMAW) is a method widely used in industrial manufacturing for steel structures and maintenance in the marine, automotive, aerospace, and construction industries [1]. In SMAW, an electric arc is formed between the electrode and the workpiece to create a molten weld pool. This method is particularly valued for its versatility, simplicity, and effectiveness in various environments [2,3].

When compared to other welding processes, SMAW exhibits distinct advantages. SMAW can be used on various materials, including stainless and low-carbon steel, making it suitable for diverse applications [4]. SMAW is a widespread fusion welding process that uses an electric arc. SMAW is a welding technique developed for manual arc welding [5]. SMAW is a low-cost technique compared to other welding processes [6]. Compared to other processes, SMAW may have lower welding quality and speed accuracy, which affect weld geometry and mechanical properties [7]. Nanomaterials have applications in numerous areas. To enhance the soundness of SMAW, many studies have focused on the addition of nanoparticles to the compositions of coating electrodes [8,9]. Nano-modifying additives, such as TiN nanoparticles, have been found to refine the grain structures of welded joints, resulting in improved tensile strength and overall mechanical performance [10]. Conversely, nano-silica coatings have been shown to enhance moisture resistance without negatively impacting the tensile properties of the weld metal [11]. The addition of TiO_2 nanoparticles has been linked to increased impact toughness in mild steel welding joints, demonstrating the potential for nanotechnology to enhance mechanical properties [12]. In other works, boron additives in a welding electrode coating enhanced a weld joint's mechanical properties [13]. The benefit of adding TiO_2 nanoparticles to electrodes, increasing welding joints' impact toughness by 42.36%, was reported by Ali et al. [14]. Sapozhkov et al. [15] doped electrodes by Ti, Zr, and Cs nanopowder to welding electrodes, which enhanced arcing stability and improved weld joint strength. The nanostructured titanium carbonitrides added to the welding electrode coatings refined the microstructure, decreased the grain boundary energy, and significantly increased the impact toughness of weld joints [16]. Nanostructured functional ceramics are added to electrodes to enhance arc stability and create a more homogeneous structure, resulting in sound weld joints [17]. The oxide ceramics used in electrode coatings significantly improve electrical conductivity [17]. Moreover, the nanostructured method minimizes deformation and cracking during welding processes [18,19]. Welding electrodes doped by boron carbide, tungsten carbide, or niobium carbide in SiC ceramics enhance thermal conductivity, improving performance, strength, and resistance to high temperatures and wear [20]. Adding Y_2O_3 to AlN ceramics increases thermal conductivity by reducing phonon scattering at grain boundaries, improving welding electrode heat transfer efficiency [21]. The high thermal conductivity in welding electrodes can be achieved by adding ultra-low B and C to SiC ceramics by reducing impurities, promoting densification, and optimizing the microstructure [22]. Miao et al. [23] suggested that nanostructured functional ceramics such as Y_2O_3 and $MgSiN_2$ in Si_3N_4 additives can positively influence the thermal conductivity of welding electrodes. The effects of the ZKHM grade have been reported in many works [24]. At an industrial scale, The Big Solar Furnace (BSF) cannot ensure the production of NFCs to meet industrial needs. To overcome this drawback, a new additive, a ZB-1-grade photocatalyst of nanostructured functional ceramics (PNFC), was developed using pulsed radiation generated by functional ceramics based on lanthanum chromite [25–28]. This work explored the thermal and mechanical stability of nanostructured ceramics.

ZKHM and ZB-1 are different grades of nanostructured functional ceramics that were introduced into the coating contents of MR-3 electrodes. ZKHM and ZB-1 were obtained in various ways: ZKHM was obtained in a solar furnace, and ZB-1 was obtained by the mechanochemical method. This work shows these additive's impacts on the welding and technological properties of the electrode brand MR-3.

There are global restrictions on products that are harmful to the environment. More regulations are implemented to save current and future lives. Choosing environmentally friendly products is necessary for a sustainable life and economy [29]. Researchers' efforts are focused on techniques and products that ensure the sustainability of life. The coating products proposed for use in electrodes are safe for the operator and the environment. The additives proposed for use in electrode coatings improve electrode performance and can be used for surfacing, welding, and repair work. The IE technique used to elaborate the ZB-1 brand is the patented method that was used to fabricate the new electrode coating for the first time. Moreover, this technique allows manufacturers to produce additives for nanostructured functional ceramics on a large scale. IE technology is attributed to an effect related to a quantum-mechanical phenomenon known as the Impulse Tunneling Effect (ITE), in which a particle or wave can overcome a potential by accumulating significant energy momentum. According to de Broglie's hypothesis, the momentum of any type of particle can be used to determine its wavelength by the formula $\lambda = h/p$, where λ is the wavelength, h is Planck's constant, and p is the particle's momentum. When a large energy momentum accumulates, for example, in the form of photons, a particle's wavelength significantly decreases. These "short-wavelength" particles can tune through a potential barrier, overcoming it even when their energy is below the height of the barrier itself.

Unlike the standard tunneling effect, in ITE, all photons that strike the functional ceramics are utilized and converted to the required wavelength. Thus, ITE allows for the effective use of radiation energy by focusing momentum, with the effective power of photons exceeding their actual energy. Furthermore, ITE generates a very narrow energy range associated with the rising edge of the impulse. By precisely tuning the impulse front according to the energy of the target process, ITE acts highly selectively, directing all impulse energy into the narrow necessary range. This enables the maximum efficiency of the melting capacity of the welding arc through optimal alignment of impulse characteristics and required energy. On the other hand, IE technology allows for the treatment of material with IE generated from such ceramic. Using functional ceramic radiation to calcine welding electrodes enables coatings with high-quality welding and technological properties to be obtained while saving energy and reducing the calcination time compared to standard technologies such as electric furnaces [30].

This work was a comparative analysis of the effectiveness of PNFC when added in small quantities (from 0 to 8%) to the composition of the MR-3 electrode from the point of view of welding and technological properties.

2. Materials and Methods

The PNFC under the ZKHM brand was manufactured by BSF according to US patent No. 5,350,927 [26]. However, the PNFC brand ZB-1 was fabricated using IR radiation according to US patent No. 5,472,720 [27]. Both additives in the electrode coatings were made from the mixture of powders depicted in Table 1, which had a granulometric composition of 2–10 microns. The content of the 5-micron fraction was at least 50%.

Table 1. Chemical composition of additives ZKHM and ZB-1.

Additives	**FeO%**	**SiO_2%**	**CaO%**	**CrO_3%**	**AlO%**	**MgO%**	**CuO%**
Percentages (%)	35	28	15	13.5	3.5	3	2

The flow chart in Figure 1 shows the steps of electrode preparation.

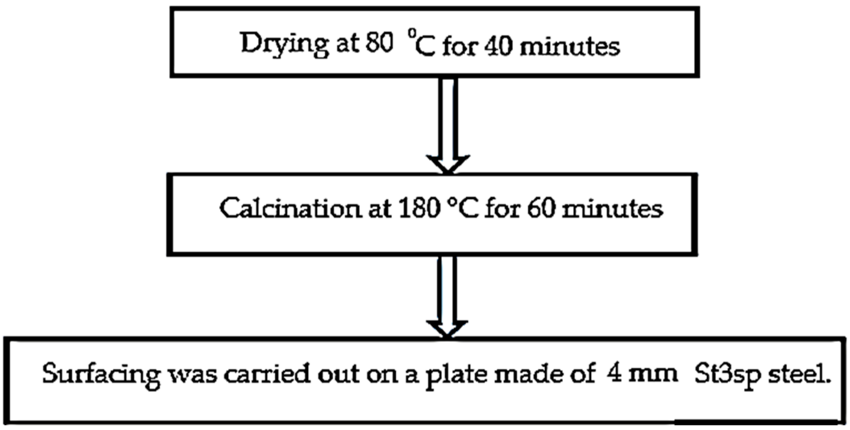


Figure 1. Electrode preparation steps.

The tests were conducted under a 140 A alternating current. Figure 2 shows the setup of the experiment, which allowed measurement of the breaking length of the arc ("L_{bla}"), representing the length of the gap between the end of the electrode and the plate formed after surfacing.

The height of the peak at the end of the electrode ("h_k") is depicted in Figure 3. This indicator was related to the method and the calcination modes.

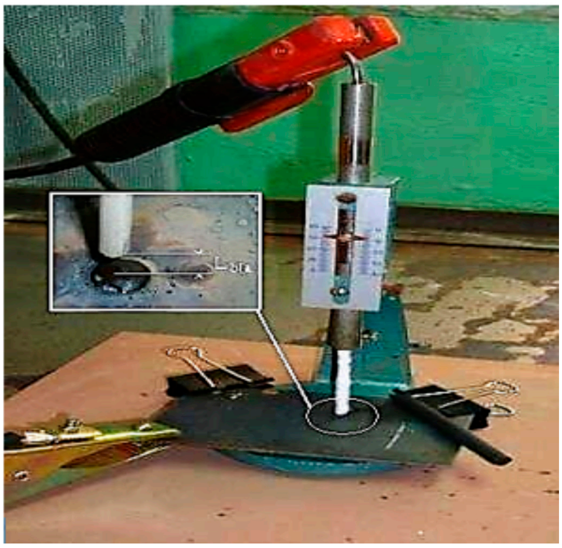


Figure 2. The installation for the determination of the breaking length of the arc ("Lbla").

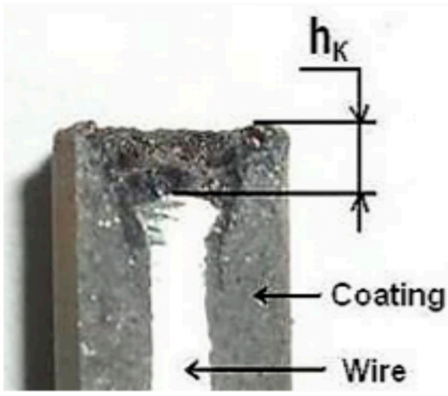


Figure 3. The visor at the end of the electrode ("hk").

Other indicators are specified in Table 2.

Table 2. Welding and technological indicators.

$\alpha_p = \frac{G_p}{I \times t}$	The metal melting coefficient	The electrode fused quantity coefficient
$\alpha_H = \frac{G_H}{I \times t}$	The surfacing coefficient	The surfacing coefficient
$\psi = \frac{\alpha_p - \alpha_H}{\alpha p} \times 100$	The loss coefficient	Losses are due to spattering and oxidation.

G_p and G_H are the mass of electrode metal melted and the mass of electrode metal deposited, respectively, during time t (measured in grams). I—welding current value, A; t—arc burning time, hours.

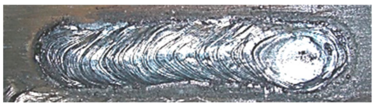
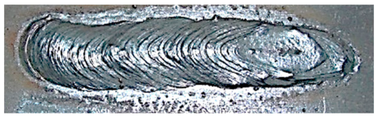
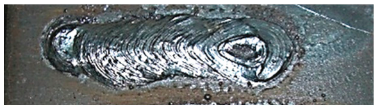
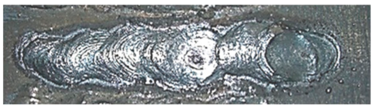
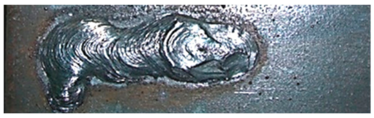
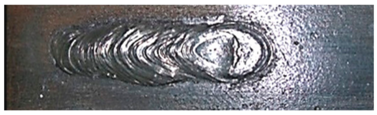
These welding and technological properties of the welding electrodes were determined according to a method described in many works [28,31–33].

The performance of the new electrodes was assessed using the coefficient of determination (R^2) [34]. The coefficient of determination (R^2) measures the strength of the linear correlation between the studied modes and properties. Polynomial approximating curves were used to construct dependency graphs.

3. Results and Discussion

Comparative results for the formation of deposited welds showed that welds obtained by surfacing with electrodes with the PNFC additives ZKHM and ZB-1 at concentrations up to 1% were distinguished by high-quality formation without external defects. When welding with electrodes containing more than 1% PNFC, deterioration in the quality of the formation of the deposited beads was observed in both cases. The outcomes of this study for both brands are given in Table 3 and Figures 4–8.

Table 3. External aspects of joints performed with electrodes coated with PNFC additives ZKHM and ZB-1.

No.	Amount of ZKHM Additive in MR-3 Electrode Coating, %	External Aspects of SWAM Joints Performed with ZKHM Additive	Amount of ZB-1 Additive in MR-3 Electrode Coating, %	External Aspects of SWAM Joints Performed with ZB-1 Additive
1	1		1	
2	2		2	
3	4		4	
4	8		8	

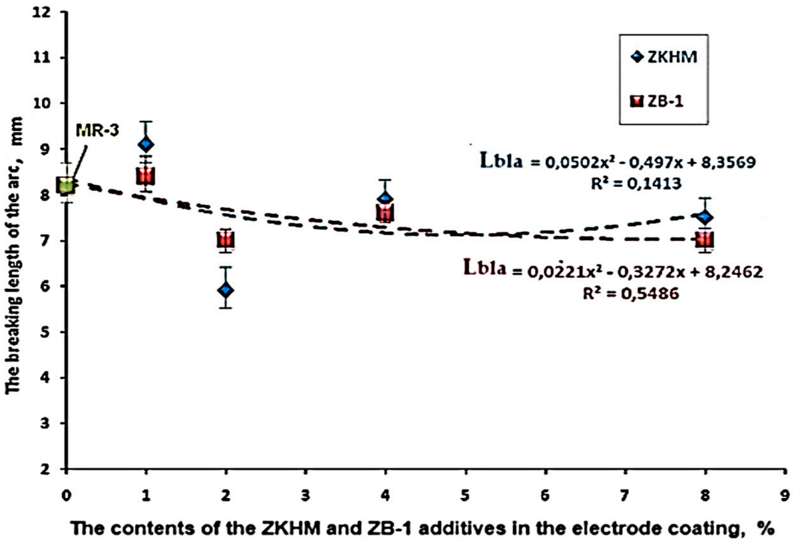


Figure 4. The dependence of the arc breaking length ("L_{bla}") on the contents of the ZKHM and ZB-1 additives in the MR-3 electrode coating.

According to the results presented in Table 4, with a PNFC content of up to 1%, the breaking length of the arc increased when welding with electrodes with the additives ZKHM and ZB-1. A further increase in the amount of either additive in the composition of the PNFC coating worsened the stability of arc combustion, characterized by a decrease in the breaking length of the arc ("L_{bla}").

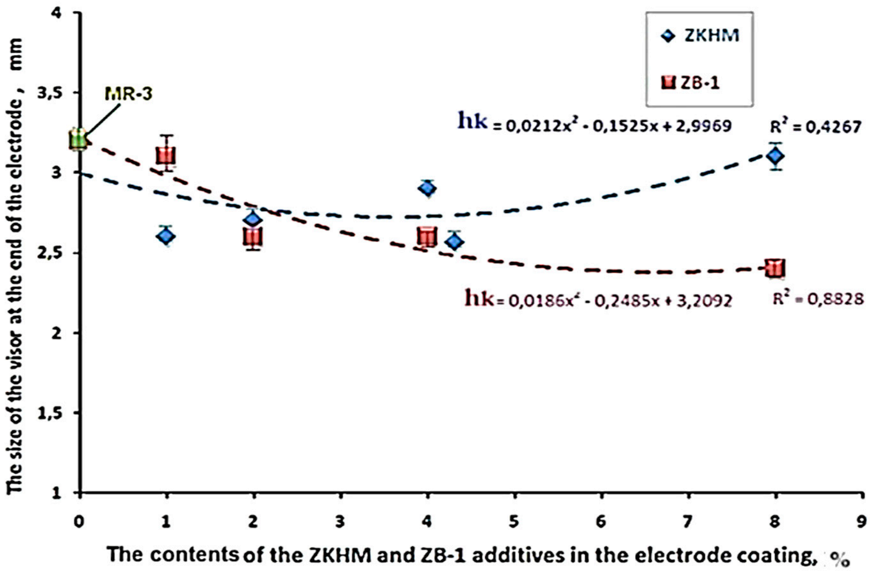


Figure 5. The dependence of the "h_k" indicator on the proportion of the ZKHM and ZB-1 additives in the MR-3 electrode coating.

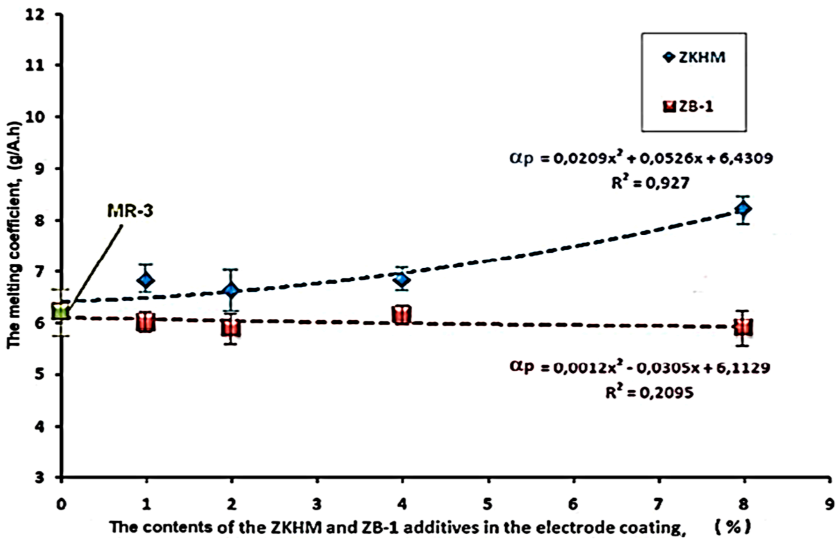


Figure 6. The dependence of the melting coefficient ("α_p") on the proportions of the ZKHM and ZB-1 additives in the MR-3 electrode coating.

We noticed that the standard deviation was less than one regardless of the welding or technological property under study, which can be considered an indication that the tests were performed in good conditions. These results confirmed small fluctuations between the minimum and maximum obtained values. The standard deviation was low, which attested to the results' reliability.

The curve of the dependence of the breaking length of the arc ("L_{bla}") (see Figure 4) on the content of the ZB-1 additive in the electrode coating (R^2 = 0.548) shows a stronger correlation between these indicators than for the electrode with the ZKHM additive (R^2 = 0.141). The improvements in the formation of deposited welds and the stability of the arcs of the welding electrodes can be explained by the fact that with small additions of the PNFC additives ZKHM and ZB-1 to the composition of the electrode coating up to a concentration of 1%, they played the role of surfactants and helped reduce the surface tension of the drop at the end of the electrode. This facilitated the separation of droplets from the end of the electrode and the metal transfer process during welding from large droplets to small droplets [35], which contributed to an increase in the breaking length of the arc and the high-quality formation of the deposited welds. However, increasing the contents of these additives above 1% led to an increase in the release of the gas phase during welding and a decrease in the effect of the surfactant, worsening the stability of the arc and the formation of the weld bead.

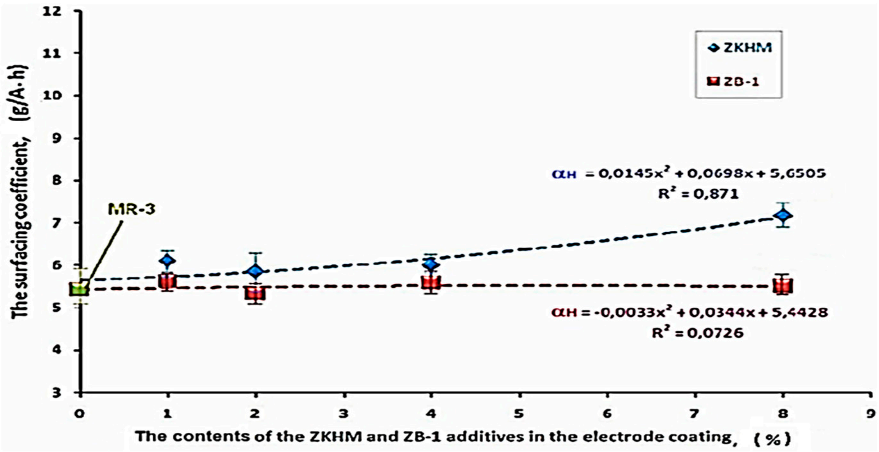


Figure 7. The dependence of the surfacing coefficient ("α_H") on the proportions of the ZKHM and ZB-1 additives in the MR-3 electrode coating.

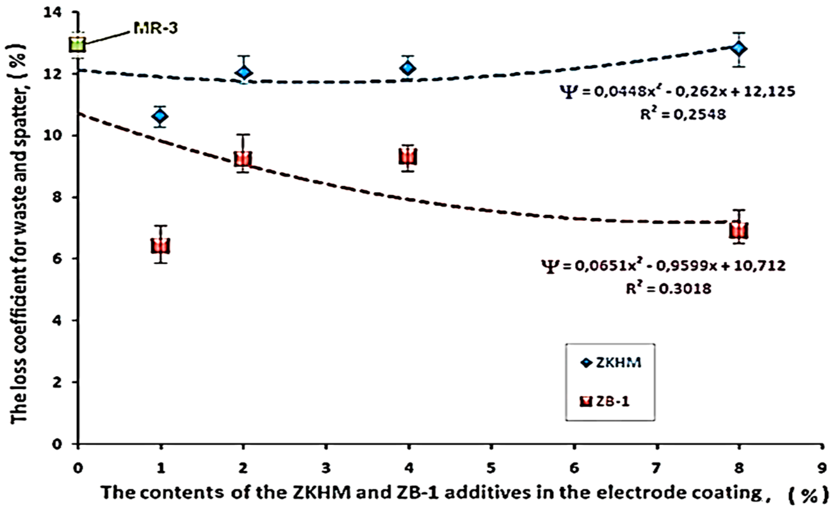


Figure 8. The effect of the ZKHM and ZB-1 proportions in the MR-3 electrode coating on the "ψ" indicator.

The values in the above table are the arithmetic means of three measurements. Interesting results were observed in a comparative analysis of the influence of PNFC additives obtained by various methods on the "h_k" indicator. The effect of the PNFC additives on "h_k" showed a robust correlation with the addition of the ZB-1 brand (R^2 = 0.849) and a strong correlation with the addition of the additive ZKHM (R^2 = 0.465). Despite this, the effect of the additives on this indicator differed depending on the brand of PNFC and the quantity of their coating composition. Thus, the addition of the PNFC additive ZKHM up to a concentration of 2% reduced the size of the visor, and a further increase increased this value (see Figure 5). The addition of ZB-1-brand PNFC to the coating reduced the "h_k" indicator, and the higher its content in the electrode coating, the more effective it was. At the same time, "h_k" decreased by 25% when the content of the additive ZB-1 was as high as 8%.

Table 4. Welding and technological properties of welding electrode brands MR-3, ZKHM, and ZB-1.

Welding Electrode Brand and NFCs	Additive NFC Proportions in MR-3 Coating (%)	Breaking Length of Arc of Welding Electrode (mm)		Size of Visor at End of Electrode (mm)		Metal Melting Coefficient (g/A·h)		Surfacing Coefficient (g/A·h)		Loss Coefficient for Waste and Spatter (%)	
		Average	**Standard Deviation**	**Average**	**Standard Deviation**	**Average**	**Standard Deviation**	**Average**	**Standard Deviation**	**Average**	**Standard Deviation**
MR-3	0	8.2	0.82	3.2	0.46	6.22	0.87	5.41	0.88	12.90	0.50
ZKHM	1	9.1	0.95	2.6	0.26	6.82	0.5	6.10	0.46	10.60	0.40
	2	5.9	0.95	2.7	0.36	6.63	0.75	5.85	0.84	12.00	0.56
	4	7.9	0.78	2.9	0.20	6.83	0.42	6.00	0.41	12.20	0.44
	8	7.5	0.82	3.1	0.44	8.22	0.50	7.17	0.54	12.80	0.70
ZB-1	1	8.4	0.75	3.1	0.60	6.01	0.35	5.62	0.37	6.40	0.75
	2	7.0	0.56	2.6	0.44	5.90	0.55	5.33	0.46	9.20	0.75
	4	7.6	0.46	2.6	0.26	6.16	0.34	5.59	0.48	9.30	0.50
	8	7.0	0.60	2.4	0.25	5.92	0.64	5.50	0.46	6.90	0.66

A different picture of the influence of PNFC on the size of the visor ("h_k") was observed with the addition of the PNFC additive ZKHM. When adding ZKHM in small quantities up to 2%, the peak value of "h_k" decreased, and a further increase in the ZKHM content led to an increase in this value. This effect appears to be explained by the fact that a ZKHM additive concentration of more than 2% increased the melting temperature of the electrode coating and caused it to melt more slowly than the metal electrode rod. As a result, the "h_k" indicator increased.

As shown in Figure 6, the influence of the ZKHM additive on the melting coefficient ("α_p") had a very strong correlation (R^2 = 0.927), and this value increased throughout the entire studied range, as the maximum value was observed when the concentration of ZKHM was 8% (see Figure 6). On the contrary, welding electrodes with PFNC additives from the ZB-1 brand had a weak correlation with the melting coefficient ("α_p") (R^2 = 0.209) and slightly reduced this indicator.

The influence of the PFNC additives on the deposition coefficient ("α_H") had correlations and dependencies similar to the melting coefficient ("α_H") (see Figure 7).

Analysis of the results of the influence of the PNFC additives ZKHM and ZB-1 on the coefficients of melting and deposition showed a larger effect of the additive ZKHM on these indicators; i.e., it helped to increase molten electrode metal and increased the productivity of the welding process. Figure 8 shows weak correlations with the "ψ" indicator when PNFC were added to the electrode coating. According to the data obtained, the largest effect on losses due to waste and spattering was observed when adding ZB-1-grade PNFC to the composition of the electrode coating, which reduced this indicator regardless of this additive's content. This indicator's largest reduction (44.5%) was detected when the content of the PNFC additive ZB-1 was 1%. A minor decrease in the coefficient of loss due to waste and spattering ("ψ") was also observed when adding the PNFC additive ZKHM to the coating up to a concentration of 1%. Further increases in the concentration of this additive led to increasing welding electrode losses during the welding process.

It is known that the moisture remaining in a coating deteriorates such welding and technological properties of welding electrodes as spattering and uneven melting [36]. In this regard, the effect of reducing losses due to waste and spattering when introducing PNFC can be explained by their ability to heat the coating during welding, which contributes to the efficient removal of residual moisture in the coating after the heat treatment of the welding electrodes.

4. Conclusions

This study aimed to compare the effectiveness of PNFC additives synthesized in the BSF (brand: "ZKHM") and in an IR radiation furnace (brand: "ZB-1"), and the influence of these additives on welding performance was revealed. In particular, a small effect of an NFC additive on the melting ability of the SMAW process was observed. Thus, the depth of weld penetration increased twofold when using electrodes with NFC additives compared to welding with known MR-3 electrodes. Also, losses due to burnout and spatter were reduced by 70%, which met the industrial requirements.

The IE technique is beneficial for large-scale industrial production. It is recommended to use additives from the photocatalyst brand "ZB-1" since adding PNFC from either brand to coatings at concentrations up to 1% increased the breaking length of the arc ("L_{bla}").

A comparative analysis of the size of the visor ("h_k") indicated different effects for the PNFC brands. The ZKHM photocatalyst reduced this indicator at concentrations up to 2%, and at higher concentrations this indicator increased steadily. The ZB-1-grade NFC reduced the "h_k" indicator, and the higher its content in the electrode coating, the more effective it was. Simultaneously, the "h_k" indicator was reduced to 25% when the content of the ZB-1 additive was as high as 8%. The coefficients of metal melting ("α_p") and surfacing ("α_H") increased steadily and reached their highest values when the ZKHM concentration was 8%. On the contrary, welding electrodes with the NFC additive ZB-1 significantly reduced these indicators.

The loss coefficient ("ψ") was significantly reduced (by 44.5%) when the content of the ZB-1 additive was 1%. A slight decrease in this coefficient was observed when the ZKHM additive was added to the coating up to a concentration of 1%.

The welds performed with electrodes containing ZKHM- and ZB-1-grade PNFC up to concentrations of 1% showed high-quality formation without external defects. The ZB-1 additive in the welding electrode coatings improves their welding and technological properties and can be used for surfacing, welding, and repair work. Further research is needed to identify the underlying physical mechanisms.

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