A Study of the Influence of Additives of Nanostructured Functional Ceramics in the Coating of Welding Electrodes on their Welding and Technological Properties

Rustam Saidov
Institute of Material Sciences of the Uzbekistan Academy of Sciences, Uzbekistan
saidov_r@yahoo.com

Rustam Rakhimov
Institute of Material Sciences of the Uzbekistan Academy of Sciences, Uzbekistan
rustam-shsul@yandex.com

Kamel Touileb
Department of Mechanical Engineering, College of Engineering in Al-Kharj, Prince Sattam bin Abdulaziz University, P.O. 655, Al-Kharj 16273, Saudi Arabia
K.touileb@psau.edu.sa (corresponding author)

Sanjar Abduraimov
Institute of Material Sciences of the Uzbekistan Academy of Sciences, Uzbekistan
abduraimovsanjar1992@gmail.com

Received: 14 August 2024 | Revised: 13 September 2024 | Accepted: 27 September 2024

ABSTRACT

The present work aims to study the influence of Nanostructured Functional Ceramics Photocatalysts (PNFC) under the brand name ZB-2, obtained using a synthesis method deploying pulsed radiation activation technology on welding and technological properties. This method of obtaining ceramic material allows the latter to be produced on an industrial scale. Therefore, it can replace the technology for producing PNFC under the influence of concentrated solar radiation at the Big Solar Furnace (BSF) of the Institute of Materials Science, Academy of Sciences of the Republic of Uzbekistan. The ZB-2 ceramic material has shown its effectiveness when used as an additive in the coating charge of the MR-3 welding electrode. Thus, the breaking arc length of the MR-3 welding electrode is increased up to 2% with the addition of ZB-2 to the coating charge. With additions of more than 2%, the breaking arc length decreases. The additive ZB-2 has the same effect on the diameter of the deposited point of the MP-3 welding electrode. When its content in the coating is up to 2%, the diameter of the deposited point increases, and a further increase in the additive content reduces this indicator. Adding up to 1% ZB-2 into the coating composition has a beneficial effect on the size of the peak at the end of the electrode. When its content exceeds 1%, the latter decreases. Also, an increase in the content of the PNFC additive in the coating of the MR-3 electrode reduces the value of the melting coefficient and increases the value of the deposition coefficient, which contributes to a sharp reduction in losses due to waste and spattering up to 53% when the additive content in the coating mass is up to 8%.

Keywords-manual arc welding; welding electrodes; Nanostructured Functional Ceramics (NFC)

I. INTRODUCTION

Welding processes and equipment are constantly evolving to meet industry needs and requirements. The former can only be valid, though, if they meet the regulations and standards that ensure the quality and safety of joints. Many research works have been dedicated to welding processes and equipment development to achieve safer and economically efficient products concerning standards and regulations [1-3]. The Manual Metal Arc (MMA) welding process, usually named coated electrode welding, refers to when the heat provided to the workpiece is generated by an electric arc established between the end of the electrode and the near-surface of the workpieces to be joined. The electrode consists of a metal core and a flux coating. The electrode is readily melted and consumed in the form of droplets. The coated flux ensures the arc stability and protects the weld pool from air gases [4]. The MMA process is the cheapest and most popular technique used in many industries [5]. Owing to nanomaterial varieties and properties, the former's employment in different industrial fields, such as the power plant, building, agriculture, medicine, industry, defense, radio electronics, power engineering, information systems, transport, and biotechnology sectors, has grown significantly during this last decade. Moreover, nanomaterials can be fabricated to the desired size, shape, and with the required properties [6]. The application of nanopowders would greatly improve the currently available technological procedures and would create qualitatively new production processes. Authors in [7] demonstrated that a nanosized powder of a refractory compound, such as titanium carbide or nitride, produces laser welding joints with greatly improved strength properties. The structure of the welded joints changes from needle-dendritic to quasi-equiaxed and fine-dispersion. The mechanical properties, strength and plasticity, of the welded metal are enhanced. The application of nanostructured materials has been expanded to the diffusion bonding of creep-resisting nickel alloys in pressure welding. In that study the nanostructured, crystalline monoliths of Ni_3Al and $NiAl_3$ intermetallic compounds were used.

The main findings revealed that the application of an intermediate layer in the form of films activates the process of diffusion bonding of nickel alloys [8]. The joint produced via diffusion bonding, without the nanolayer, contained a brittle interlayer reducing the strength, and the structure of the joint with the nanolayer (Ti/Al, thickness 20 mm) resembled those of the parent metal. The absence of pores and cracks in the weld zone and the HAZ indicates that the quality of the welded joint is high [9]. Nanopowders, such as welding electrodes, are also used in other areas of the welding production. Authors in [10] proposed varying the production process of MMA welding electrodes via adding nanopowder Ti, Zr, and Cs to electrode components through liquid glass. These additives support arcing stability, improve the strength of a weld joint, and, consequently, increase the quality of a weld joint and the structure overall. There is not much information published on the use of nanostructured materials in welding production. However, in recent years, research into the utilization of nanopowders in the welding industry has increased. Adding nanopowder to liquid glass is one of the existing ways to enhance the mechanical properties of welding metal through applying nano-disperse materials (nanopowders). There are several methods of adding nanopowder to a welding pool, but the most effective one involves adding nanopowder to liquid glass, i.e. at the stage of electrode production. So, nanopowders are powders with characteristic nano-sizing causing distinct changes in their properties [11]. Nanopowders are deployed to obtain fine-grained-structured weld metal; when crystallized, these additives ensure grain refinement and ultimately improve the mechanical properties without changing the chemical composition of the alloy. It has been determined that the structure of the metal welded with experimental electrodes is more dispersed and homogenous than the uneven structure of the metal welded with serial electrodes [12]. Ceramic materials have improved thermal, chemical, and physical stability. Ceramic materials of the formula $RCrO_3$, where R is a rare earth oxide, such as yttrium oxide, are typically used. These materials, such as electrodes, although useful in electroconductive applications, suffer from low chemical stability when exposed to temperatures above 1600°C, low resistance to thermal cycling at temperatures above 1500°C, and the inability to be heated at high heating rates. These deficiencies have limited their use in applications where property stability is important. Therefore, there is a need for rare earth oxide ceramic materials that have improved stability and are useful in electroconductive applications, as well as in high-temperature environments [13]. The effect of adding Nanostructured Functional Ceramics (NFC) was studied in [10]. It was used to charge electrode coatings, consisting of Fe_3O_4-CaO-TiO_2 oxides, and calcining. Welding electrodes with Infrared Radiation (IR), generated by functional ceramics on the welding and technological properties of the welding electrode were studied in [14].

The results of the aforementioned works revealed the beneficial effect of small ZKHM additives and heat treatment of welding electrodes using IR radiation on the welding and technological properties of welding electrodes, such as the breaking length of the arc L_{bla}, the diameter of the deposited point $Ø_{dp,}$ and especially the losses factor for waste and splashing of electrode metal ψ. However, from a practical and economic point of view, BSF cannot ensure the production of NFC on an industrial scale. The Institute of Materials Science has developed a technology for obtaining a PNFC using conventional technology, by mixing and thermos-synthesis of oxides, followed by activation utilizing pulsed radiation generated by functional ceramics based on lanthanum chromite [15]. This technology makes it possible to synthesize the target material in the required volumes. Therefore, from a practical point of view, the method developed at the Institute of Materials Science for producing PNFC based on the solid-phase method from a mixture of appropriate oxides, followed by activation by pulsed radiation, it is the most appropriate technique. There are NFC photocatalysts of several ZB brands (ZB-1, ZB-2, etc.). Thus, the use of the PNFC brand ZB-1 as an additive in the coating of welding electrodes made it possible to improve the quality of these welding electrodes [16]. The purpose of this work is to study the effect of small additives (from 0% to 8%) of the ZB-2 PNFC in the coating composition of the well-known brand welding electrode MR-3 on welding and technological properties. Nanomaterials are still new in the welding production sector. Therefore, the publications in the field are not as numerous as expected. This paper is an interesting contribution to the addition of NFC in consumable coating electrodes. On the other hand, the novelty in this work is the methodology used to produce such electrodes.

II. EXPERIMENT PROCEDURE

In this study, the MMA, a fusion welding process, was deployed. Arc welding is established between a consumed electrode and the welding pool. The protection of the weld pool comes from the electrode itself. The coating forms slag, protecting the transferring drops and the weld pool from deleterious atmospheric gases, such as oxygen, nitrogen, and hydrogen [17]. Both direct current as well as alternating current can be used for MMA welding, but not all the stock electrode's coating types can be welded with alternating current, for instance, purely basic electrodes cannot be utilized [18]. During MMA welding, only the current is adjusted. Arc voltage is derived from the arc length, which the welder must maintain. The current-carrying capacity of the electrode diameter must be taken into consideration when adjusting the current. As a rule, the lower limits apply to the welding of root passes and for Flat Position (FP), while the upper limits apply to the other positions, filler passes, and final passes. As the current increases, the deposition rate and the associated welding speed also increase. Penetration also increases with the current. The specified currents apply only to non-alloyed and low-alloy steels. When high-alloy steels and nickel-based alloys are employed, lower values must be selected due to the higher electrical resistance. The following rules for the calculation of individual intensity currents must be respected:

- For a 3.2 mm diameter, the current range is 90 - 150 A.
- For a 4.0 mm diameter, the current range is 120 - 200 A.
- For a 5.0 mm diameter, the current range is 180 - 200 A.

To conduct this research, an NFC photocatalyst of the ZB-2 brand [19] was added to the coating charge of the welding electrode MR-3. The ZB-2 photocatalyst consisted of a mixture of powders based on chromium oxide (44.7%), with additives of iron oxides (28%), silicon dioxide (17%), calcium oxide (5.5%), aluminum oxide (2.5%), magnesium oxide (2%) and copper oxide (0.3%), with a particle size distribution of 2–10 microns with a fraction of 5 microns of at least 50%. The ZB-2 photocatalyst was synthesized using the following steps:

1. Preparation of a charge of the specified composition.
2. Mixing in a planetary mill in an aqueous environment for 5 hours.
3. Subsequent drying and annealing at a temperature of 800°C for 2 hours and subsequent cooling in the furnace.
4. Grinding in a planetary mill for 5 hours.
5. Annealing at 1000°C for 2 hours, followed by cooling in the furnace.
6. Annealing at 1200°C for 2 hours, followed by cooling in the furnace.
7. The resulting powder was placed for 15 minutes under emitters coated with functional ceramics based on lanthanum chromite (MC-1), generating pulsed radiation.

The coating for the welding electrodes of the MR-3 brand was obtained from the manufacturer. The production of MR-3 electrodes of the MR-3 grade is regulated by the requirements and provisions of GOST 9466-75, GOST 9467-75, and ТУ 1272-002-58965179-2006. Based on these standards, the filler material belongs to the E46 type. The above-cited electrodes are used for the welding of structural low-alloy carbon steels with a carbon content of greater than 0.25%. The slag base of the MR-3 welding electrode is a ternary system of TiO_2-SiO_2-CaO oxides with a Basicity Index (BI) of 0.27. The coatings on welding electrodes were obtained by dipping the Sv08A wire, 4 mm in diameter, into a coating mass consisting of a coating mixture of an MR-3 welding electrode, with additions of ZB-2 NFC photocatalyst ZB-2 ranging from 0% to 8%. The coating mass was obtained through mixing the investigated charge mixture (with a granulometric composition of not more than 315 μm) with liquid glass (density 1.4 g/cm3 and module 2.5) in a ratio that promotes the formation of a coating layer on the surface of the metal rod, with thickness (D/d) 1.4 mm –1.6 mm. After applying the coating, the electrodes were dried at a temperature of 80 C for 40 min and calcined at a temperature of 180 C for 60 min. Surfacing was carried out on a plate made of St3sp steel, 4 mm thick, using an inverter-type rectifier of the Jasic TIG-200P type from Jasic Technology Company, Shenzhen, China. The welding arc was powered by alternating current at a welding current level of 140 A. The welding and technological properties of welding electrodes include the stability of the burning of the arc of the welding electrode or the breaking length of the arc L_{bla}, the diameter of the deposited point $ø_{dp}$ or the quality of its formation, and the size of the visor at the end of the electrode h_k. These welding and technological properties of welding electrodes were determined following the method described in former research works [20]. An indicator of the stable arc burning of welding electrodes is the breaking length of the arc L_{bla}, which was determined using the installation shown in Figure 1(a). The value of L_{bla} was determined by measuring the distance between the end of the electrode and the plate formed after surfacing, as can be observed in Figure 1(b).

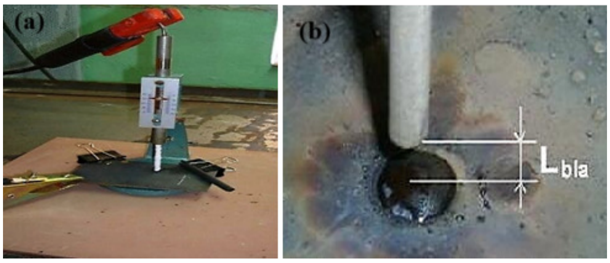

Fig. 1. Installation for testing to determine the breaking length of the arc (a) and the breaking length of the arc L_{bla} (b).

The influence of the method and calcination modes on the tendency of welding electrodes to form a peak was assessed using the height of the peak at the end of the electrode h_k, as depicted in Figure 2. The quality of the welded joint formation was assessed by the deposited beads, as portrayed in Figure 3, as well as by the shape and diameter of the deposited point $ø_{dp}$, as displayed in Figure 4. A correct formation of the deposited point without such external defects, namely undercuts, burns, cracks, and pores, indicates the high-quality formation of the welded joint.

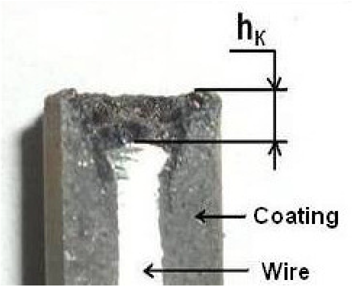

Fig. 2. Visor at the end of the electrode h_k.

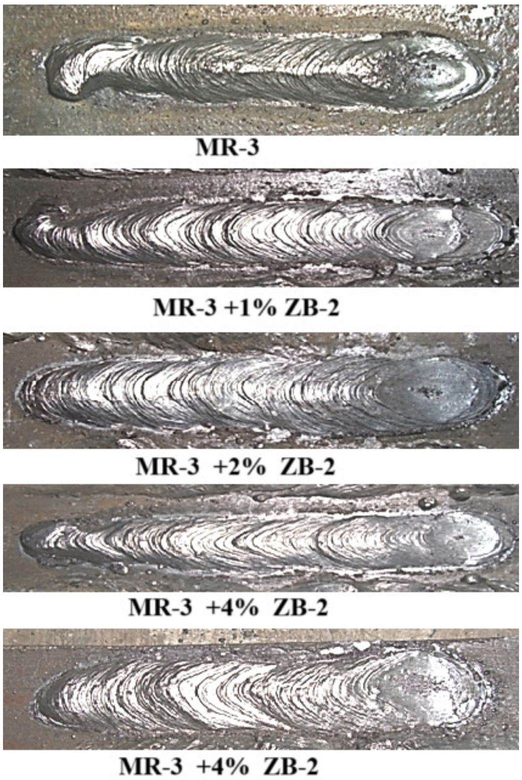

Fig. 3. The appearance of weld beads made with experimental welding electrodes obtained from a mixture of MR-3 charge and ZB-2 photocatalyst additives.

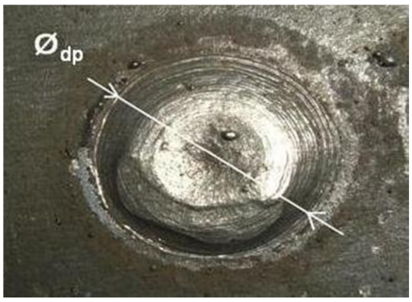

Fig. 4. View of the deposited point.

Also, studies were carried out on the effect of ZB-2 photocatalyst on the metal melting coefficient α_p, the deposition coefficient a_H, and the losses factor for waste and splashing of electrode metal Ψ, characterizing the processes of welding and surfacing and determined by/based on the method described in [21]. To estimate the magnitude of these losses due to spattering, oxidation, and evaporation (fumes) during the burning of the arc, the so-called loss coefficient for waste and spatter Ψ was used, which is determined by:

$$\Psi = \frac{\alpha_p - \alpha_H}{\alpha_p} \times 100\% \qquad (1)$$

Also, studies were carried out on the effect of ZB-2 photocatalyst on the metal melting coefficient α_p, the deposition coefficient $\alpha_{H,}$ and the loss factor for waste and splashing of electrode metal Ψ, characterizing the process of welding and surfacing determined by the following method. In (2) the metal melting coefficient α_p shows how much electrode metal is melted per unit time per ampere of welding current, and is determined by:

$$\alpha_p = \frac{G_p}{I.t} \qquad (2)$$

where G_P is the mass of electrode metal melted during time t, g. I, is the welding current value, A. t, is the arc burning time in hours, and α_p is the metal melting coefficient, g/(A·h).

The melting coefficient depends on the electrode material, the composition of its coating, type, polarity, and current density. In addition, during the welding process, the electrode heats up, which also affects the melting intensity of the electrode metal. Before welding begins, the electrode is at room temperature; by the end of welding, it can heat up to 500 °C. To evaluate the surfacing process, the deposition coefficient α_H is used, determined by:

$$\alpha_H = \frac{G_H}{I.t} \qquad (3)$$

where G_H is the mass of deposited electrode metal during time t, g. I is the welding current value, A. t is the arc burning time, hours, and α_H is the deposition coefficient, g/(A·h).

The loss coefficient for waste and spatter Ψ depends on the composition of the electrode and its coating, the welding mode, and the type of welded joint. For example, the loss factor increases with increasing current density and arc length. Typically, the value of Ψ lies in the range:

- from 1% to 3% for submerged arc welding.
- from 3% to 6% when welding in shielding gases.
- from 5% to 10% when welding with thickly coated electrodes.
- from 10% to 20% when welding with thin-coated electrodes.

For values greater than 20% of the loss coefficient, it is not advisable to use electrode welding. The degree of influence of the ZB-2 photocatalyst additive in the electrode coating on the welding and technological properties of welding electrodes was evaluated using the coefficient of determination R^2 [22]. The coefficient of determinism is in the range of $0<R^2<1$ and indicates the strength of the linear correlation between the modes and properties under study when used in constructing dependency graphs and polynomial approximating curves.

III. RESULTS AND DISCUSSIONS

The results of the studies on the influence of coating compositions on the welding and technological properties of welding electrodes are given in Table I and in Figures 5-10.

TABLE I. RESULTS

#	**The amount of additive ZB-2 in the composition of the MR-3 coating %**	**L_{bla}, [mm]**	**$ø_{dp}$, [mm]**	**h_k [mm]**	**α_p [g/A·h]**	**$\alpha_н$ [g/A·h]**	**Ψ [%]**
1	0	7.1	11.8	2.1	6.62	5.42	18.1
2	1	7.3	11.1	1.9	6.41	5.65	11.7
3	2	8.2	12.1	2.3	6.67	5.79	13
4	4	6.5	11.2	2.3	6.09	5.49	10.1
5	8	7.1	10.7	2.2	6.24	5.72	8.5

It can be noticed that each value provided in Table I corresponds to the arithmetic mean of the results of three measurements.

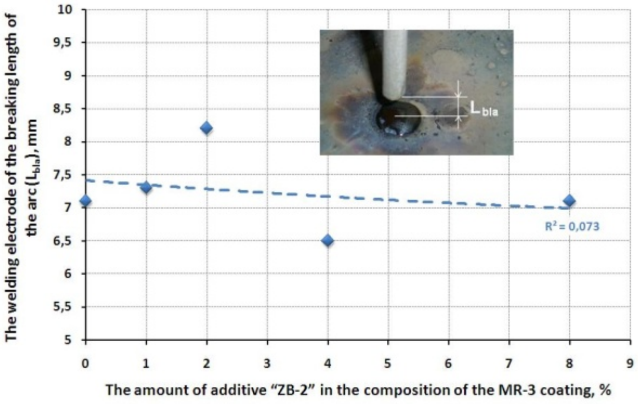

Fig. 5. Dependence of the breaking length of the arc L_{bla} on the content of the additive ZB-2 in the electrode coating.

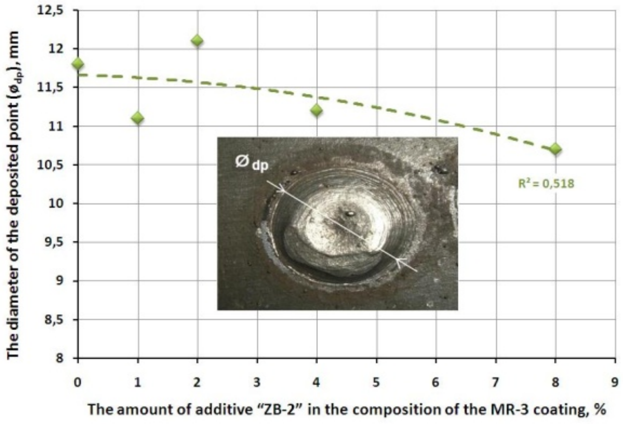

Fig. 6. Dependence of the diameter of the deposited point $ø_{dp}$ on the content of the additive ZB-2 in the electrode coating.

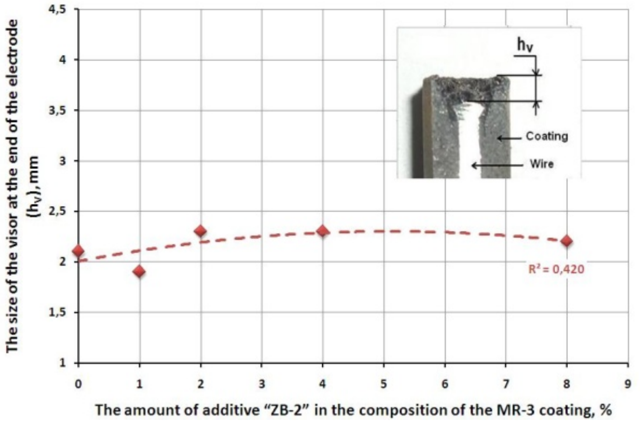

Fig. 7. Dependence of the end of the electrode h_k on the content of the additive ZB-2 in the electrode coating.

According to the results presented in Table I and Figure 5, the length of the deposited bead and an increase in the value of the breaking length of the arc L_{bla} is observed when the content of the ZB-2 photocatalyst additive is up to 2%. A further increase in the additive content in the composition of the coating reduces the breaking length of the arc.

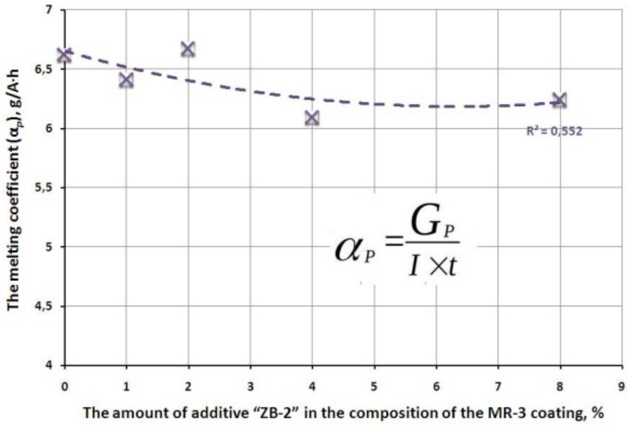

Fig. 8. Dependence of the melting coefficient α_p on the content of the additive ZB-2 in the electrode coating.

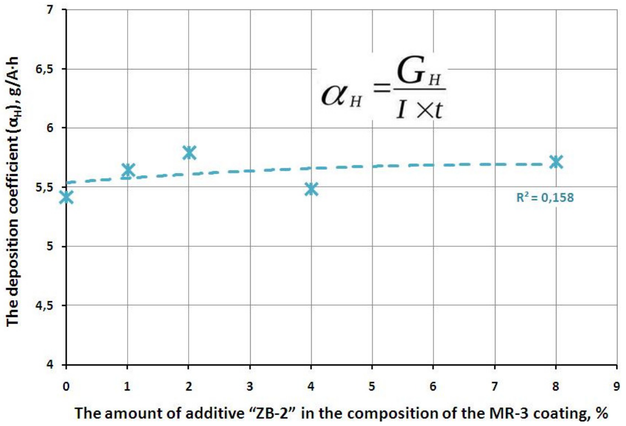

Fig. 9. Dependence of the deposition coefficient α_H on the content of the additive ZB-2 in the electrode coating.

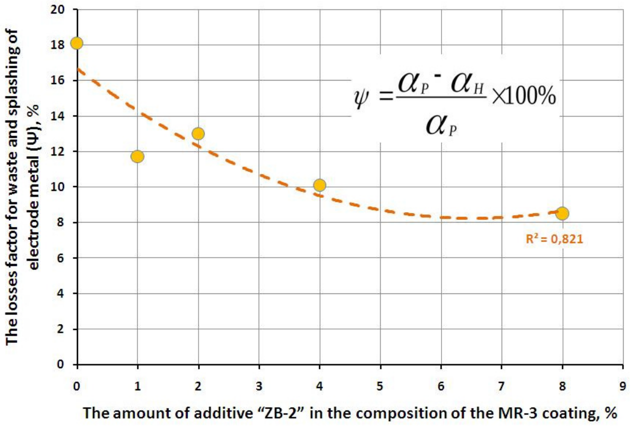

Fig. 10. Dependence of the losses factor for waste and splashing of electrode metal Ψ on the content of the ZB-2 additive in the electrode coating.

The study of the ZB-2 additive's influence on the diameter of the deposited point $ø_{dp}$, presented in Figure 6, demonstrated its/the latter's strong correlation dependence on the content of the ZB-2 additive in the electrode coating ($R^2 = 0.518$). When the former's content in the coating is up to 2%, the diameter of the deposited point increases, and a further increase in the additive content reduces this indicator, i.e. the formation of the deposited weld deteriorates. According to the results outlined in Figures 5 and 6, the nature of the curves relates to the dependencies of the breaking length of the arc, and the diameter of the deposited point on the content of ZB-2 additives, which are identical. The specific effect of the ZB-2 additives can be explained by the fact that when its content is up to 2%, it plays the role of a surfactant and reduces the surface tension of the drop at the end of the electrode. At the same time, the separation of droplets from the end of the electrode is facilitated and the process of metal transfer during welding goes from large droplets to small droplets, which contributes to an increase in the breaking length of the arc and the high-quality formation of the deposited weld. When the content of this additive is above 2%, it helps increase the release of the gas phase during the welding process, which reduces the effect of the surfactant, impairing the stability of the arc and the formation of the weld bead. A moderate correlation is observed between the content of ZB-2 additives in the composition of the electrode coating mixture and the size of the peak at the end of the electrode h_k ($R^2 = 0.420$), as displayed in Figure 7. At the same time, when the additive content is up to 1%, the h_k value decreases, but with an increase in its content of above 1%, it increases. This effect is apparently explained by the fact that additives of more than 1% increase the melting temperature of the electrode coating and contribute to its slower melting compared to the metal electrode rod. As a result, the size of the visor at the end of the electrode increases. However, these changes in the height of the electrode end cap are insignificant (up to 0.2 mm) and do not affect the stable combustion of the welding arc. As disclosed by the results of the studies presented in Figures 8-10, the influence of ZB-2 additives in the electrode coating has a strong correlation with the melting coefficient α_p ($R^2 = 0.552$), a weak correlation with the deposition coefficient $\alpha_н$ ($R^2 = 0.158$), and a very strong one with the loss coefficient due to waste and splashing ψ (R^2=0.821). At the same time, with increasing the addition of ZB-2, the value of the melting coefficient αp decreases, and the value of the deposition coefficient αн increases. The loss coefficient due to waste and splashing ψ drops sharply to 53% when the additive content in the coating mass is up to 8%. The effect of a sharp decrease in the loss coefficient ψ is apparently associated with the ability of ZB-2 additives to generate pulsed radiation during heating of the coating during welding. This facilitates the effective removal of residual moisture from the electrode coating after heat treatment of welding electrodes and reduces the spattering and uneven melting of the electrode.

IV. CONCLUSIONS

The present investigation aims to study the influence of Nanostructured Functional Ceramics Photocatalysts (PNFC) under the brand name ZB-2, obtained using a synthesis method, which utilizes pulsed radiation activation technology on welding and technological properties. The main findings are summarized as follows:

- An increase in the breaking arc length L_{bla} of the MR-3 welding electrode was revealed with the addition of ZB-2 to the coating charge in an amount of up to 2%. With additions of more than 2%, the breaking arc length decreases.
- The additive ZB-2 has the same effect on the diameter of the deposited point $ø_{dp}$ in the welding electrode MR-3. When its content in the coating is up to 2%, the diameter of the deposited point increases, and a further increase in the additive content reduces this indicator.
- It has been established that the introduction of the ZB-2 additive of up to 1% into the coating of the MR-3 electrode has a beneficial effect on the size of the peak at the end of the electrode h_k. When its content is over 1%, the value of h_k decreases.
- It was also revealed that with an increase in the content of the PNFC additive in the coating of the MR-3 electrode, the value of the melting coefficient αp decreases, and the value of the deposition coefficient αн increases. This contributes to a sharp reduction in losses due to waste and spattering ψ during welding to 53%, with an additive content in the coating mass of up to 8%.

REFERENCES

[1] A. B. Pereira and F. J. M. Q. de Melo, "Quality Assessment and Process Management of Welded Joints in Metal Construction—A Review," *Metals*, vol. 10, no. 1, Jan. 2020, Art. no. 115, https://doi.org/10.3390/met10010115.

[2] A. Hdhibi, K. Touileb, R. Djoudjou, A. Ouis, M. L. Bouazizi, and J. Chakhari, "Effect of Single Oxide Fluxes on Morphology and Mechanical Properties of ATIG on 316 L Austenitic Stainless Steel Welds," *Engineering, Technology & Applied Science Research*, vol. 8, no. 3, pp. 3064–3072, Jun. 2018, https://doi.org/10.48084/etasr.2097.

[3] A. Alzahougi, B. Demir, and M. Elitas, "An Optimization Study on Resistance Spot Welding of DP600 Sheet Steel via Experiment and Statistical Analysis," *Engineering, Technology & Applied Science Research*, vol. 13, no. 4, pp. 11106–11111, Aug. 2023, https://doi.org/10.48084/etasr.5804.

[4] I. M.-B. Omiogbemi *et al.*, "Mechanical properties and corrosion behavior of duplex stainless steel weldment using novel electrodes," *Scientific Reports*, vol. 12, no. 1, Dec. 2022, Art. no. 22405, https://doi.org/10.1038/s41598-022-26974-6.

[5] A. Hussein and A. Al-Joubori, "Welding of ferritic stainless steel plate using austenitic stainless steel electrode," *IOP Conference Series: Materials Science and Engineering*, vol. 745, no. 1, Oct. 2020, Art. no. 012083, https://doi.org/10.1088/1757-899X/745/1/012083.

[6] P. H. C. Camargo, K. G. Satyanarayana, and F. Wypych, "Nanocomposites: synthesis, structure, properties and new application opportunities," *Materials Research*, vol. 12, pp. 1–39, Mar. 2009, https://doi.org/10.1590/S1516-14392009000100002.

[7] N. Yu. Krampit, "Methods of controlling melting and transfer of electrode metal (review)," *Welding International*, vol. 24, no. 10, pp. 808–812, Oct. 2010, https://doi.org/10.1080/09507116.2010.486194.

[8] K. Sampath, "Analysis of a High-Strength Steel SMAW Database," *Welding Journal*, vol. 100, no. 12, pp. 410–420, Dec. 2021, https://doi.org/10.29391/2022.101.036.

[9] A. Ustinov, I. Falchenko, A. Ishchenko, G. K. Kharchenko, T. V. Melnichenko, and A. N. Muraveynik, "Diffusion welding of γ-TiAl based alloys through nano-layered foil of Ti/Al system," *Intermetallics*, vol. 16, pp. 1043–1045, Aug. 2008, https://doi.org/10.1016/j.intermet.2008.05.002.

[10] S. B. Sapozhkov and E. M. Burakova, "The Study of Complex (Ti, Zr, Cs) Nanopowder Influencing the Effective Ionization Potential of Arc Discharge When Mma Welding," *IOP Conference Series: Materials Science and Engineering*, vol. 142, no. 1, Dec. 2016, Art. no. 012018, https://doi.org/10.1088/1757-899X/142/1/012018.

[11] M. A. Kuznetsov and E. A. Zernin, "Nanotechnologies and nanomaterials in welding production (review)," *Welding International*, vol. 26, no. 4, pp. 311–313, Apr. 2012, https://doi.org/10.1080/09507116.2011.606158.

[12] S. V. Makarov and S. B. Sapozhkov, "Use of Complex Nanopowder (Al2O3, Si, Ni, Ti, W) in Production of Electrodes for Manual Arc Welding," *World Applied Sciences Journal 22*, pp. 87–90, 2013, https://doi.org/DOI: 10.5829/idosi.wasj.2013.22.tt.22145.

[13] R. K. Rakhimov and E. V. Kim, "Radiation emitting ceramic materials and devices containing same," US5350927A, Sep. 27, 1994.

[14] Institute of Material Sciences, SPA "Physics-Sun", Uzbekistan Academy of Sciences, Tashkent, Republic of Uzbekistan *et al.*, "A new method for drying and calcining welding electrodes using emitters made of functional ceramic," *COMPUTATIONAL NANOTECHNOLOGY*, vol. 7, no. 1, pp. 44–51, Mar. 2020, https://doi.org/10.33693/2313-223X-2020-7-1-44-51.

[15] R. M. Saidov, С. Р. Маннапович, R. K. Rakhimov, Р. Р. Хакимович, F. M. Rakhimova, and Р. Ф. Маратовна, "Results of the Application of Functional Ceramics in Composition of the Fe3O4-CaO2-TiO2 Slag System for Welding Electrode Coatings," *Computational nanotechnology*, vol. 9, no. 3, pp. 53–59, Sep. 2022, https://doi.org/10.33693/2313-223X-2022-9-3-53-59.

[16] S. M. Rustam, R. K. Rustam, and K. Touileb, "The Effect of Nanostructured Functional Ceramics Additives on the Properties of Welding Electrodes," *Metals*, vol. 13, no. 11, Nov. 2023, Art. no. 1849, https://doi.org/10.3390/met13111849.

[17] N. Fujiyama and G. Shigesato, "Effects of Mn and Al on Acicular Ferrite Formation in SAW Weld Metal," *ISIJ International*, vol. 61, no. 5, pp. 1614–1622, 2021, https://doi.org/10.2355/isijinternational.ISIJINT-2020-407.

[18] S. Mahajan and R. Chhibber, "Design and Development of Shielded Metal Arc Welding (SMAW) Electrode Coatings Using a CaO-CaF2-SiO2 and CaO-SiO2-Al2O3 Flux System," *JOM*, vol. 71, no. 7, pp. 2435–2444, Jul. 2019, https://doi.org/10.1007/s11837-019-03494-9.

[19] R. K. Rakhimov and E. V. Kim, "Treatment of materials with infrared radiation," US5472720A, Dec. 05, 1995.

[20] Yu. N. Saraev, D. A. Chinakhov, D. I. Ilyashchenko, A. S. Kiselev, and A. S. Gordynets, "Investigation of the stability of melting and electrode metal transfer in consumable electrode arc welding using power sources with different dynamic characteristics," *Welding International*, vol. 31, no. 10, pp. 784–790, Oct. 2017, https://doi.org/10.1080/09507116.2017.1343977.

[21] D. P. Il'yaschenko, I. I. Chebotarev, and S. B. Sapozhkov, "Characteristics of droplet transfer of electrode metal during MMA depending on the chemical composition of the material of the rod of the coated electrode," *IOP Conference Series: Materials Science and Engineering*, vol. 939, no. 1, Jun. 2020, Art. no. 012028, https://doi.org/10.1088/1757-899X/939/1/012028.

[22] R. Saidov, K. Höfer, M. Kusch, K. Rustamovna, D. Gulamova, and N. Avezova, "Investigation of the peculiarities of the formation of the weld beads on highly resistant steels during A-TIG welding – Part 2: Influences of the physical and chemical properties of activating fluxes on the formation of the weld beads during TIG and A-TIG welding," *Welding and Cutting*, no. 4, pp. 264–271, Nov. 2022, https://doi.org/10.53192/WAC202204264.