

# The effect of heat input on mass fraction of nanocomponents fed into the weld pool

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**Abstract.** It is shown that surfacing with feeding Nano oxides or Nano carbides into the weld pool leads to significant increase the wear resistance of deposited metal. Meanwhile, the information available in the literature on the optimal concentrations of Nano components corresponds only to specific surfacing conditions. Other surfacing conditions require additional experimental studies to determine optimal concentrations under these new conditions. Theoretical studies revealed that a change in the heat input of surfacing is accompanied by a change in the volume and mass of the weld pool, which leads to the changes in the mass concentrations of Nano components. It is shown that, the volume and mass of the weld pool may change almost by 3 times, and the mass percentage of Nano components by 2 times. A method has been proposed for determining the mass fraction of Nano components in the weld pool at different heat inputs of surfacing. The experimental studies confirmed analytical predictions. The use of the proposed technique will make it possible to spread the technology of surfacing with feeding of Nano components into the weld pool without additional experimental studies.

**Keywords:** weld pool, deposited metal, wear resistance, Nano components, heat input, mass concentration.

## 1. Introduction

One of the most common technological processes for reconditioning of the worn parts is an electrical arc surfacing, which achieves the desired working layer on the surface of the product [1]. Surfacing process effectively restores the worn surfaces of friction units and allows their further exploitation. However, considering limited service life due to hard working conditions, it is issue of the day to develop the technology that would allow to increase wear resistance not changing equipment and consumables which are used at the enterprises.

This requirement is met by the technology based on feeding Nano particles into the weld pool and changing during crystallization the structural-phase state of the metal and its properties. The technology hold great potential for substituting currently used restoration technology, in addition to their potential significantly increase wear resistance

not changing existing at enterprises consumables and equipment.

Recently published studies show that the feeding of refractory compounds in the form of Nano oxides or Nano carbides directly into the weld pool qualitatively changes the structure and properties of both the weld and the deposited metal. The results of research of the structure and properties of low-alloyed high-strengths weld metal are summarized in [2].

The main objective of feeding Nanoparticles into the weld pool during surfacing is increasing the wear resistance of the deposited metal. It has been found that the effect of increasing wear resistance is observed in low-alloyed, medium- and highly-alloyed compositions. Thus, in highly alloyed compositions the wear resistance increases by 2,5 times, medium alloyed by 3 times, and low alloyed by almost 5 times [3], [4], [6]. It has been shown that SiO<sub>2</sub> Nano oxide is the most effective for increasing the wear resistance of the deposited metal compared to Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> Nano oxides and TiC Nano carbide [3], [5]. Moreover, increasing the wear resistance is observed regardless of the schemes of feeding Nanoparticles into the weld pool which meet the requirements bypassing the high-temperature zone of the arc [7].

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The data available in the literature were obtained empirically and are aimed at revealing the effect of Nano particles on the properties of the deposited metal under specific experimental conditions. In these works, Nano components were fed into the weld pool in different mass fractions in order to determine the optimal value, that is, the experiments were performed under conditions of specific values of heat input with variations only in the values of the amount of Nano oxides or Nano carbides.

In practice, the heat input of surfacing varies widely depending on the specific conditions of surfacing of products. The change in heat input leads to a change in the dimensional parameters and, accordingly, the mass and volume of the weld pool. The previously established optimal values of the mass fraction of nanoparticles were obtained under specific experimental conditions at fixed values of heat input and, accordingly, the volume and mass of the weld pool. With their change, in order to maintain the same optimal effect on the structure and properties of the deposited metal, the mass fraction of Nanoparticles should also be changed, since it is established in relation to the mass of the weld pool.

The lack of regularities between the amount of nanoparticles in the weld pool and the wear resistance of the deposited metal under conditions of changes in heat input of surfacing requires additional experimental studies in each specific case, which limits the use of this technology. In this regard, it is important to determine the values of the mass fractions of Nano components under changing surfacing conditions.

The purpose of the work is to determine the amount of Nano components fed into the weld pool for various values of heat input during surfacing.

## 2. Theoretical studies

Changes in heat input of surfacing lead to the changes in dimensional parameters and, accordingly, the mass and volume of the weld pool. Term heat input per unit length of bead  $q_h$  refers to the ratio  $q/v_s$ . To determine the thermal power  $q$  and the heat input of the surfacing  $q_h$ , and the volume of the weld pool  $V_p$  the well-known formulas of the welding processes theory are used:

$$q = \eta \cdot I \cdot U, \quad \text{J}, \quad (1)$$

$$q_h = \eta \cdot I \cdot U / v_s, \quad \text{J} \cdot \text{m}^{-1}, \quad (2)$$

where  $I$  – arc current, A;  $U$  – arc voltage, V;  $v_s$  – surfacing speed, m/s;  $\eta$  – efficiency coefficient.

$$V_p = \frac{q^2}{8\pi\lambda c\rho v (T_m - T_0)^2}, \quad (\text{m}^3). \quad (3)$$

where  $\lambda$  – coefficient of thermal conductivity,  $\text{W} \cdot \text{m}^{-1} \cdot \text{°C}$ ;  $c\rho$  – heat capacity,  $\text{J} \cdot \text{m}^{-3} \cdot \text{°C}$ ;  $T_m$  – melting temperature,  $\text{°C}$ ;  $T_0$  – initial temperature,  $\text{°C}$ .

The amount of Nano components in the weld pool can be determined by their concentration, in particular, as mass or volume fraction.

The mass fraction  $M_x$  or mass percentage is determined by the ratio of the mass of Nano components in the weld pool ( $m_{np}$ ) to the total mass of weld pool ( $m_p$ ):

$$M_x = \frac{m_{np}}{m_p} \times 100\%. \quad (4)$$

Liquid metal mass in the pool:

$$m_p = \rho \cdot V_p, \quad \text{g}. \quad (5)$$

Mass of Nano components per unit length of the bead:

$$m_n = \frac{m_k}{l_p}, \quad (\text{g} \cdot \text{m}^{-1}), \quad (6)$$

where  $m_k$  – mass of components fed into the weld pool in each case, g;  $l_p$  – the length of the modified bead, m.

Theoretical mass of Nano components in the pool:

$$m_{np} = m_n \cdot L, \quad \text{g}. \quad (7)$$

The calculations are based on the mode parameters used in the experiments and the parameters most often used during surfacing by self-shielding flux-cored wire, solid wire in shielding gases and under flux.

The amount of Nano components is calculated per 90 mm ( $m_c$ ) of the deposited metal (as in the experiments). Nano powders have an extremely low density, for example, silicon dioxide –  $0.00031 \text{ g/cm}^3$ , so it is enough to change the value of their initial concentrations from 0.01 g to 0,1 g, which is consistent with literature data. The initial data for calculating the parameters of the weld pool are given in Table 1.

**Table 1.** Output data for calculations of weld pool parameters in the MathCAD mathematical package

Heat capacity, $\text{J} \cdot \text{m}^{-3} \cdot \text{°C}$	$c\rho$	$4.8 \cdot 10^6$
Density of steel, $\text{g} \cdot \text{m}^{-3}$	$\rho$	7810
Thermal conductivity coefficient, $\text{W} \cdot \text{m}^{-1} \cdot \text{°C}$	$\lambda$	41,9
Efficiency coefficient	$\eta$	0.8
Naper's number (base of natural logarithms)	$e$	2.718
Melting point, $\text{°C}$	$T_m$	1480
Initial temperature, $\text{°C}$	$T_0$	20
Plate thickness, m	$\delta$	0.01

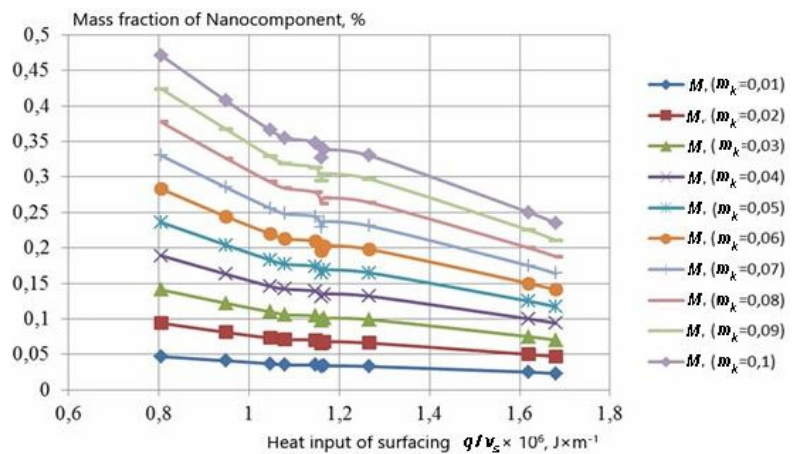
The results of determining the mass fractions of Nano components depending on the surfacing conditions are shown in Table 2.

**Table 2.** The main mode parameters of surfacing and the results of determining the mass fractions of Nano components

	1	2	3	4	5	6	7	8	9	10
$I, A$	180	200	220	180	200	220	225	270	270	300
$U, V$	28	20	27	28	30	25	32	27	27	30
$v_s, m \cdot h^{-1}$	18	11	18	12.5	16	12,5	18,08	18	12,5	16
$(m \cdot c^{-1})$	$5 \times 10^{-3}$	$3.056 \times 10^{-3}$	$5 \times 10^{-3}$	$3.472 \times 10^{-3}$	$4.444 \times 10^{-3}$	$3.472 \times 10^{-3}$	$5.022 \times 10^{-3}$	$5 \times 10^{-3}$	$3.472 \times 10^{-3}$	$4.444 \times 10^{-3}$
$q, J$	4032	3200	4752	4032	4800	4400	5760	5832	5832	7200
$q/v_s, J \cdot m^{-1}$	$0.806 \times 10^6$	$1.047 \times 10^6$	$0.95 \times 10^6$	$1.161 \times 10^6$	$1.08 \times 10^6$	$1.267 \times 10^6$	$1.147 \times 10^6$	$1.166 \times 10^6$	$1.68 \times 10^6$	$1.62 \times 10^6$
$v_p, m^3$	$3.018 \times 10^{-7}$	$3.11 \times 10^{-7}$	$4.192 \times 10^{-7}$	$4.345 \times 10^{-7}$	$4.811 \times 10^{-7}$	$5.175 \times 10^{-7}$	$6.131 \times 10^{-7}$	$6.313 \times 10^{-7}$	$9.091 \times 10^{-7}$	$10.83 \times 10^{-7}$
$m_p, g$	2.357	2.429	3.274	3.394	3.758	4.042	4.788	4.931	7.1	8.455
$M_1, (m_k = 0,01)$	0.047	0.037	0.041	0.033	0.035	0.033	0.035	0.034	0.023	0.025
$M_2, (m_k = 0,02)$	0.094	0.073	0.081	0.065	0.07	0.066	0.07	0.068	0.047	0.05
$M_3, (m_k = 0,03)$	0.141	0.11	0.122	0.098	0.106	0.099	0.104	0.101	0.07	0.075
$M_4, (m_k = 0,04)$	0.189	0.146	0.163	0.131	0.142	0.132	0.139	0.135	0.094	0.1
$M_5, (m_k = 0,05)$	0.236	0.183	0.204	0.164	0.177	0.165	0.174	0.169	0.117	0.125
$M_6, (m_k = 0,06)$	0.283	0.22	0.244	0.196	0.213	0.198	0.209	0.203	0.141	0.15
$M_7, (m_k = 0,07)$	0.33	0.256	0.285	0.229	0.248	0.231	0.244	0.237	0.164	0.175
$M_8, (m_k = 0,08)$	0.377	0.293	0.326	0.262	0.284	0.264	0.278	0.27	0.188	0.2
$M_9, (m_k = 0,09)$	0.424	0.329	0.367	0.295	0.319	0.297	0.31	0.304	0.211	0.225
$M_{10}, (m_k = 0,1)$	0.471	0.366	0.407	0.327	0.36	0.33	0.348	0.338	0.235	0.25

The data in Table 2 indicate significant changes in the volume and mass of the weld pool with a change in heat input of surfacing. Thus, the volume of the weld pool  $V_p = 3.018 \times 10^{-7} m^3$  at  $q/v_s = 0.806 \times 10^6 J \cdot m^{-1}$  increases more than by 3 times and is  $V_p = 10.83 \times 10^{-7} m^3$  at  $q/v_s = 1.62 \times 10^6 J \cdot m^{-1}$ . The same thing happens with the change in mass of the pool. Its values at the indicated heat input of surfacing also change more than 3 times and are  $m_p = 2.357 g$  and  $m_p = 8.455 g$  respectively. These regularities are also reflected in changes in the mass percentage of Nano components in the weld pool.

Fig. 1 shows the effect of heat input of surfacing on the mass fraction of Nano components with different its concentration fed into the weld pool. Data analysis shows



**Fig. 1.** Effect of heat input on mass fraction of Nano components with different its concentrations

that regardless of the amount of Nano components, its concentration is reduced by 2 times when heat input of surfacing is doubled. For example, when  $m_k = 0.05 g$  of a Nano component is fed, its mass fraction in the weld pool at a

heat input  $q/v_s = 0.806 \times 10^6 \text{ J}\cdot\text{m}^{-1}$  is 0.283 % by mass, and at a heat input  $q/v_s = 1.62 \times 10^6 \text{ J}\cdot\text{m}^{-1}$ –0.125 % by mass.

It follows from this that in order to maintain the required concentration, it must be increased with an increase in the heat input of surfacing. Thus, in order to maintain the same concentration as  $m_k = 0.06 \text{ g}$  at a heat input  $q/v_s = 0.806 \cdot 10^6 \text{ J}\cdot\text{m}^{-1}$ , at  $q/v_s = 1 \cdot 10^6 \text{ J}\cdot\text{m}^{-1}$  it is necessary to feed into the weld pool  $m_k = 0.07 \text{ g}$  and at  $q/v_s = 1.4 \cdot 10^6 \text{ J}\cdot\text{m}^{-1}$  it is necessary to feed  $m_k = 0.09 \text{ g}$ .

It is also possible to ensure the same concentration of Nano components in the pool by feeding an initially smaller concentration only by reducing the heat input of surfacing. For example, the concentration of Nano components  $m_k = 0.03 \text{ g}$  at heat input  $q/v_s = 0.806 \cdot 10^6 \text{ J}\cdot\text{m}^{-1}$  is the same as with feeding  $m_k = 0.04 \text{ g}$  at heat input  $q/v_s = 1.147 \cdot 10^6 \text{ J}\cdot\text{m}^{-1}$ .

Thus, the data in Fig. 1 can be used as a monogram, which allows determining not only the change in mass fractions at given values of concentrations of Nano components, but also assigning corresponding changes in concentrations to maintain the desired mass percentage with a change in the heat input of surfacing.

### 3. Experimental studies

In order to identify general regularities and to confirm the results of theoretical studies, surfacing was performed using different processes and conditions. Thus, surfacing on steel 09G2S by the wire 30HGSA was performed by feeding silicon Nano oxide into the weld pool in a mixture with flux AN-60 and with paraffin as well. Surfacing on the same steel by the wire 09G2C was performed

feeding silicon Nano oxide in a mixture with flux AN-348 and using spray-technology. Chemical composition of base and deposited metal is shown in Table 3.

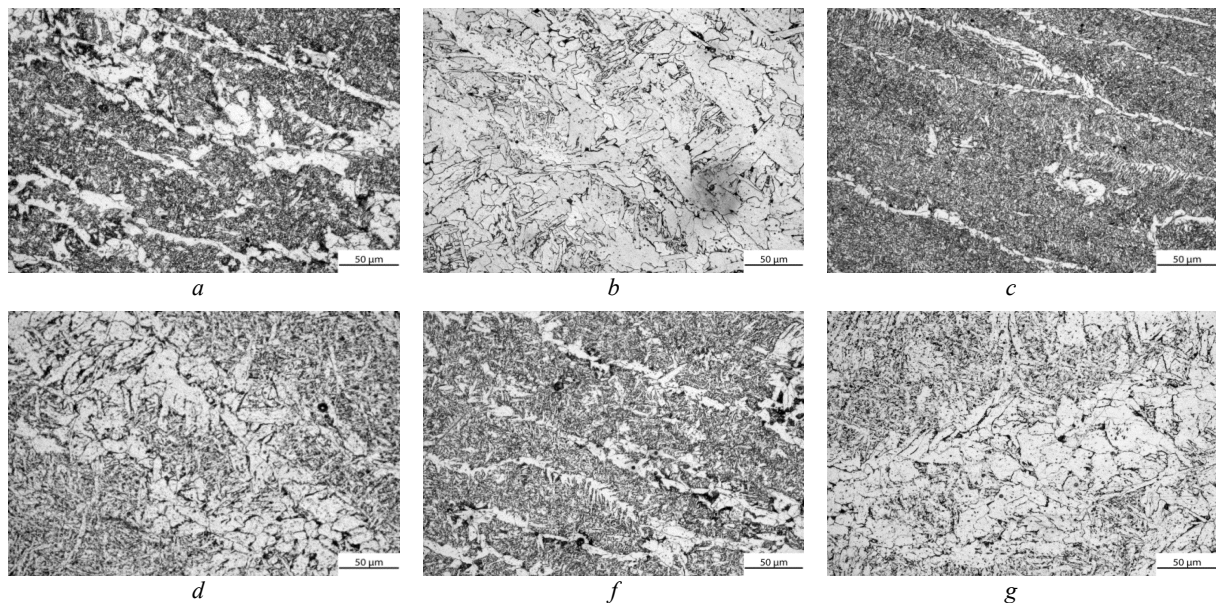
**Table 3.** Chemical composition of base and deposited metal, wt %

Elements	C	Mn	Si	Cr
St09G2C base metal	0.09	2.0	0.8	–
Metal deposited by 30HGSA wire	0.3	1.0	1.0	1.0
Metal deposited by 09G2C wire	0.08	1.9	0.8	–

Surfacing by the wire 30HGSA and by the wire 09G2C was performed in heat input  $q/v_s = 1,3 \cdot 10^6 \text{ J}\cdot\text{m}^{-1}$  and  $q/v_s = 1,6 \cdot 10^6 \text{ J}\cdot\text{m}^{-1}$ . To compare the results, structure, hardness and wear resistance were studied.

For the conditions of metal-to-metal friction, wear resistance tests were carried out according to the shaft-to-block scheme on samples 20 mm long and 10 mm wide. A 50 mm disk of steel U8 was used as a counterbody. Test conditions: pressure on the sample –  $P = 0.1 \text{ MPa}$ ; friction velocity –  $V = 0.8 \text{ m/s}$ ; test temperature –  $T = 20 \text{ }^\circ\text{C}$ ; test duration – 2 hours with measurements every 15 min. Samples were weighed before and after testing in accurate laboratory scales with 0,001 g error. Mass wear was determined as the difference between the sample mass values before and after the tests.

Our studies revealed that in the initial state the structure of deposited metal surfaced by the wire Np-30HGSA



**Fig. 2.** Structures of deposited metal on steel 09G2S: *a* – initial state by wire 30HGSA; *c* – feeding silicon nanooxide into weld pool in a mixture with flux,  $q/v_s = 1,3 \cdot 10^6 \text{ J}\cdot\text{m}^{-1}$ ; *f* – with paraffin,  $q/v_s = 1,6 \cdot 10^6 \text{ J}\cdot\text{m}^{-1}$ ; *b* – initial state by 09G2S wire; *d* – feeding silicon nanooxide into weld pool in a mixture with flux,  $q/v_s = 1,3 \cdot 10^6 \text{ J}\cdot\text{m}^{-1}$ ; *g* – by spray technology,  $q/v_s = 1,6 \cdot 10^6 \text{ J}\cdot\text{m}^{-1}$



and flux AN-60 is comprised of a mix of ferrite and pearlite. The pearlite itself consists of bands (or lamellar structure) of ferrite and cementite. The polygonal ferrite and the grain boundary ferrite is also called “allotriomorphic” ferrite, meaning that it is a ferrite without a regular faceted shape reflecting its internal crystalline structure are present (Fig. 2, *a*). The hardness of the structure is 217 HV. The mass loss of deposited metal is  $\Delta m = 0.22$  g.

Feeding into the weld pool of silicon Nano dioxide in a mixture with flux leads to the formation of very dispersed ferrite-perlite structure with small ferrite grains. Cementite particles precipitated at pearlite colonies boundaries (Fig. 2, *c*). An acicular ferrite has randomly oriented short ferrite needles with a basket weave feature. The hardness of the structure is 255 HV. The mass loss of deposited metal is  $\Delta m = 0.08$ g.

Feeding silicon Nano dioxide into the weld pool in a mixture with paraffin leads to the formation ferrite-perlite structure with more large sizes of ferrite grains in pearlite colonies and acicular ferrite (Fig. 2, *f*). The hardness of the structure is 225 HV and mass loss of deposited metal is  $\Delta m = 0.06$ g.

The structure of deposited metal surfaced by the wire 09G2C in initial state also is comprised of a mix of ferrite and pearlite but with lesser sizes of pearlite colonies and significantly greater amount of ferrite constituents (Fig. 2, *b*). The hardness of the structure is 140 HV. The mass loss of the deposited metal is  $\Delta m = 0.45$ g.

Feeding silicon Nano dioxide into the weld pool in a mixture with flux leads to the formation ferrite-perlite structure with larger amount of pearlite colonies and lesser amount of globular ferrite phase (Fig. 2, *d*). The hardness of the structure is 165 HV and the mass loss is  $\Delta m = 0.22$ g.

Feeding silicon Nano dioxide into the weld pool using spray technology leads to the formation ferrite-perlite structure that practically has the same features like the structure (Fig. 2, *d*) but only with lesser amount of pearlite phase (Fig. 2, *g*). The hardness of the structure is 187 HV.

#### 4. Discussion

The experimental studies confirmed the correctness of the proposed method for determining the mass fraction of Nano components at different heat input, regardless of the schemes of their feeding into the weld pool. Thus, when feeding silicon Nano oxide into the weld pool both in a mixture with AN-60 flux and in a mixture with paraffin at a heat input  $q/v_s = 1.3 \cdot 10^6$  J·m<sup>-1</sup> and a concentration  $m_k = 0.06$  g, the mass fraction was 2.0 %. To maintain this value of the mass fraction at a heat input  $q/v_s = 1.6 \cdot 10^6$  J·m<sup>-1</sup> according to Fig. 1 concentration was increased to  $m_k = 0.08$  g.

Structural analysis showed some increasing in the amount of ferrite phases at a concentration  $m_k = 0.08$  g (Fig. 2, *f*) as compared to the structure (Fig. 2, *c*). In our opinion, this is due to slower cooling at  $q/v_s = 1.6 \cdot 10^6$  J·m<sup>-1</sup> compared to cooling at  $q/v_s = 1.3 \cdot 10^6$  J·m<sup>-1</sup>. It is known that slower cooling from 800 °C to 500 °C promotes a more

complete decomposition of austenite with the formation of “softer” structures, in this case, increasing the amount of ferrite phase.

Meanwhile, the general regularities in changes the properties of the deposited metal when silicon dioxide nanopowder is fed into the weld pool are preserved, as indicated by data on micro hardness and wear resistance. Thus, if in the initial state the hardness of the deposited metal by 30HGSA wire was 217 HV, then at  $q/v_s = 1.3 \cdot 10^6$  J·m<sup>-1</sup> – 255 HV, at  $q/v_s = 1.6 \cdot 10^6$  J·m<sup>-1</sup> – 225 HV. A slight decrease in hardness at  $q/v_s = 1.6 \cdot 10^6$  J·m<sup>-1</sup> is precisely due to slower cooling at increased heat input.

As for wear, the corresponding changes in the concentrations of silicon dioxide nanopowder fed into the weld pool also confirm the preservation of wear resistance when the heat input changes. Thus, if in the initial state the mass loss of the deposited metal was  $\Delta m = 0.22$  g then at  $q/v_s = 1.3 \cdot 10^6$  J·m<sup>-1</sup> the mass loss decreased to  $\Delta m = 0.08$  g and at  $q/v_s = 1.6 \cdot 10^6$  J·m<sup>-1</sup> to  $\Delta m = 0.06$  g respectively.

Similar changes in the structure and properties of the deposited metal are observed when using 09G2S wire. Thus, both when feeding silicon dioxide in a mixture with A-348 flux at a heat input  $q/v_s = 1.3 \cdot 10^6$  J·m<sup>-1</sup>, and when feeding silicon dioxide using spray technology at  $q/v_s = 1.6 \cdot 10^6$  J·m<sup>-1</sup> an increase in the pearlite component is observed, which indicates a strengthening of the structure. Also, with an increase in heat input, there is a slight increase in the ferrite component (Fig. 2, *d*) in relation to the structure at a lower heat input (Fig. 2, *e*), which, as mentioned above, may be a consequence of slower cooling.

The general regularities in changing the properties of the deposited metal when silicon dioxide nanopowder is fed into the weld pool mixed with AN-348 flux and using spray technology are also preserved, as indicated by data on micro hardness and wear resistance. Thus, if in the initial state the hardness of the deposited metal by 09G2S wire was 140 HV, then after feeding of nanopowder mixed with flux into the weld pool at  $q/v_s = 1.3 \cdot 10^6$  J·m<sup>-1</sup> was 165 HV and using spray technology at  $q/v_s = 1.6 \cdot 10^6$  J·m<sup>-1</sup> – 185 HV. Accordingly, the mass loss was  $\Delta m = 0.22$  g and  $\Delta m = 0.2$  g in relation to losses  $\Delta m = 0.45$  g in initial state.

Thus, regardless of the schemes feeding Nano component into the weld pool increasing heat input with simultaneous increasing Nano component mass concentration according to monogram (Fig. 1) ensures practically the same level structural changes and properties of deposited metal. Some differences in the structures of the metal surfaced according to the schemes may be as a result not only slower cooling at increased heat input, but also of the different duration of contact of the Nano powder with the melt and, probably, unequal degree of preservation from complete melting of silicon Nano dioxide.

#### 5. Conclusions

1. It is shown that changing the modes of heat input in the range of practice surfacing, the volume and mass of

the weld pool change almost by 3 times, and the mass percentage of Nano components changes by 2 times;

2. A monogram has been developed to determine the necessary concentrations of Nano components to maintain

the desired mass percentage with a change in heat input of surfacing.

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## Вплив погонної енергії наплавлення на масову частку наноконцентів, що подаються у зварювальну ванну

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**Анотація.** Показано, що наплавлення з подачею наноксидів або нанокарбідів у зварювальну ванну призводить до значного підвищення зносостійкості наплавленого металу. Водночас, наявна в літературі інформація щодо оптимальних концентрацій наноконцентів відповідає лише конкретним умовам наплавлення. Інші умови наплавлення вимагають додаткових експериментальних досліджень для визначення оптимальних концентрацій за цих нових умов. Теоретичними дослідженнями встановлено, що зміна погонної енергії наплавлення супроводжується зміною об’єму та маси зварювальної ванни, що призводить до зміни масових концентрацій наноконцентів. Виявлено, що об’єм і маса зварювальної ванни можуть змінюватися майже у 3 рази, а масова частка наноконцентів – у 2 рази. Запропоновано метод визначення масової частки наноконцентів у зварювальній ванні за умови різних погонних енергій наплавлення. Експериментальні дослідження підтвердили аналітичні прогнози. Використання запропонованої методики дозволить поширити технологію наплавлення з подачею наноконцентів у зварювальну ванну без додаткових експериментальних досліджень.

**Ключові слова:** зварювальна ванна, наплавлений метал, зносостійкість, наноконцент, погонна енергія, масова концентрація.