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REVEALING THE INFLUENCE OF THE MODE OF CONTROLLED OSCILLATIONS OF THE LIQUID POOL ON THE SURFACED BEAD GEOMETRY

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This study investigates geometric dimensions of the weld bead produced by gas metal arc surfacing with a consumable electrode. Standard surfacing is characterized by low productivity because of the significant number of runs and the need for machining tall beads. Deep penetration causes a significant proportion of the base metal in the surfaced layer and inhomogeneity of the chemical composition. Existing approaches to controlling the geometry of the weld bead (pulsed arc modes, electrode oscillations, electromagnetic arc control) have a limited effect on the width or complicate the design of the welding head.

This work considers gas metal arc surfacing with controlled low-frequency oscillations of the workpiece with a liquid weld pool. The installation is built on an adjustable electric drive with a stepper motor with a programmable setting of the frequency and amplitude of oscillations. These parameters, together with energy parameters and speed, affect the geometric dimensions of the weld bead and the mechanical properties of the surfaced metal.

The width, height, and depth of the weld bead penetration were determined from macro-graphic cross-sections. A mathematical model of bead geometry as a function of surfacing parameters has been built by using experimental data regression analysis. The errors in predicting the width and height did not exceed 21.7% and 15%, respectively, thereby confirming its practical applicability.

Controlled oscillations were found to increase bead width by a factor of 1.5–2 and reduce bead height by up to a factor of 6 compared with vibration-free surfacing. This is attributed to redistribution of thermal energy and intensification of horizontal melt flows. Changing the weld bead geometry increases surfacing productivity and control accuracy. The method is suitable for use in adaptive welding systems

Keywords: electric arc surfacing, controlled workpiece oscillations, surfacing parameters, bead geometry, surfacing productivity

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1. Introduction

There is a large fleet of machines and mechanisms for various purposes, in particular in mechanical engineering and power equipment, the parts and assemblies of which, due to the peculiarities of use, wear out and are subject to restoration or initial processing and modification. This gives their working surfaces certain characteristics, for example, strength, heat resistance, certain frictional properties, etc. Modification and restoration of the surfaces of assemblies and parts can be car-

ried out in various ways but the most common among them are techniques of gas metal arc surfacing with a consumable electrode under automatic and semi-automatic modes [1].

The spread of the gas metal arc surfacing technique is due to the relative simplicity of the process implementation, the possibility of its implementation in almost all spatial positions, including with the use of semi-automatic machines. In addition, this technique allows the use of a fairly wide range of modes and electrode wires, solid cross-section and powder, of various purposes for different steels and obtaining

a surfaced layer with the required characteristics. One should also note the fairly high productivity of the surfacing process.

The gas metal arc surfacing process has some drawbacks. Among them, it is necessary to note the unfavorable geometric characteristics of the surfaced beads – width, height, and penetration depth, which are characteristic of the automatic surfacing process under the most common modes (current, voltage, process speed). The large height of the weld bead in the surfaced layer leads to additional costs when providing the surface with a working condition. The large penetration depth affects the excessive mixing of the base metal and the metal of the electrode wire, which causes a high proportion of the base metal in the surfaced layer and the heterogeneity of its chemical composition and properties. The width of the surfaced bead practically characterizes the productivity of the surfacing process. Its limitation under conventional modes requires a significant number of runs to restore parts with a large working surface, which increases the total thermal effect on the part and the risk of its deformation.

There are several ways to control the geometry of the weld bead. Pulsed arc welding with current modulation controls the heat input and transfer of the electrode metal but practically does not change the width of the weld bead. Mechanical oscillations of the electrode or torch across the seam increase the width of the run but complicate the design of the welding head and limit access to hard-to-reach areas of the part. Electromagnetic arc control affects the position of the arc column but requires special equipment and is sensitive to the magnetic properties of the base metal. Controlled oscillations of the workpiece itself with a liquid welding pool directly affect the hydrodynamics of the melt. The design of the welding head does not change, and there are no restrictions on the type of electrode wire or the arc burning mode.

Studies on bead formation at surfacing with controlled oscillations of the pool have a double practical value: the quality of the seam formation and the productivity of the process are simultaneously increased. Reducing the number of runs and reducing the proportion of base metal in the surfaced layer saves electrode wire and base metal, as well as reduces the thermal effect on the part.

2. Literature review and problem statement

Review of technical literature, for example [2, 3], reveals that the influence of liquid weld pool vibrations on the geometric dimensions of surfaced beads remains insufficiently studied. Most studies have been performed for high frequencies (tens and hundreds of Hz). Most work focuses on the microstructure and residual stresses, rather than on the weld bead geometry. For processes with a consumable electrode in CO₂, there is almost no systematic data on the influence of low-frequency controlled vibrations of the workpiece itself. Among the techniques influencing the results of gas metal arc surfacing with a consumable electrode, a mechanical effect on the liquid weld pool stands out. It is achieved either by vibration of the pool or by its controlled oscillations. In both cases, the structure of the surfaced metal, deformations and stresses after welding or surfacing, and mechanical properties change. In [2], the influence of local vibrations during welding of structural steels on the microstructure and mechanical behavior of welded joints is experimentally investigated. It was found that vibrations do not lead to noticeable changes in the properties of the weld, and the reduction of residual stresses

is not associated with the vibration effect on the pool. The studies were limited to the high-frequency vibration mode of the structure as a whole, while the effect of low-frequency controlled oscillations of the workpiece itself on the width, height, and depth of penetration of the surfaced bead remains unstudied. Multivariate analysis taking into account current, voltage, and deposition rate is not given in the cited work. A regression model of the weld geometry is not built.

In work [3], the mechanism of formation of crystallization centers under low-frequency mechanical vibration during arc welding of Inconel 601H was investigated. The optimal parameters that ensure an increase in hardness were determined: current 80 A, vibration frequency 100 Hz, and exposure duration 100 s. The study was conducted for arc welding with a non-consumable electrode without filler material. Therefore, the shape of the weld bead and its cross-sectional area are not the subject of analysis. For the welding of structural steel with a consumable electrode, these results provide an idea of the mechanism, but not of the geometry. In [4], vibrations are shown to refine the grain and reduce the structural heterogeneity of the surfaced metal. The work considers dissimilar welded joints, so the interest is on the impact toughness, not on the geometry of the weld bead. The effect of the vibration frequency is considered without taking into account the amplitude, direction of oscillations, and interaction with welding modes.

In [5], the positive effect of vibrations on the strength and fatigue life of welded joints of stainless steel when welding with a non-consumable electrode without filler material was shown. The object was butt joints of a thin sheet. Because of this, the width and height of the seam were formed by the geometry of the gap, and not by the vibration parameters. For surfacing on a massive part, these results cannot be directly transferred. In [6], the vibrational relaxation of stresses in welded structures for marine applications was considered. The method is effective after welding, on solid metal. The geometry of the weld bead is formed earlier, so vibrational relaxation does not affect it in principle. In [7], the effect of low-amplitude workpiece vibrations on the shape of penetration and the uniformity of the distribution of elements in the surfacing layer during pulsed arc welding with a consumable electrode in a shielding gas of low-carbon steel was experimentally investigated. Sinusoidal oscillations at a specific frequency change the shape of the penetration from finger-shaped to flat due to resonance between the droplet flow and the pool. The study was conducted for high frequencies (50–450 Hz) at amplitudes of about 0.5 μm. The influence of low-frequency oscillations at significant amplitudes on the width, height, and depth of penetration was ignored. The regression model of the weld bead geometry from the oscillation parameters is not given in the work. In [8] it is shown that transverse movements of the welding arc during surfacing reduce the reinforcement, penetration depth, and convexity index of the weld bead. With an increase in the oscillation frequency, microstructure refinement is observed. The study was performed for a process with short-circuit metal transfer at a fixed triangular trajectory and a constant amplitude of transverse arc oscillation. The case of controlled oscillations of the workpiece itself when the amplitude is varied was not considered in the work.

An installation for oscillating a flat part under automatic mode with frequency and amplitude control is described in [9]. The design of the oscillator is considered, and the prospects of its application are shown. The work does not provide a quantitative analysis of the geometric characteristics of the surfaced bead because its subject is the device itself. Regression models and optimization of modes were beyond the scope of that study.

Our review of the literature [2–9] showed that vibrations have a positive effect on the structure and properties of welded joints, but the geometry of the surfaced bead has been studied fragmentarily. There is no direct experimental data on the influence of low-frequency controlled oscillations of the workpiece (units of Hz at amplitudes in the millimeter range) on the width, height, and depth of penetration. Regression models for predicting these dimensions from the oscillation parameters and welding modes have also not been built.

The above makes it advisable to study the influence of oscillation parameters on the width, height, and depth of penetration of the weld beads.

3. The aim and objectives of the study

The aim of our study is to identify the influence of the surfacing parameters with controlled oscillations of the liquid weld pool on the geometric characteristics of the surfaced bead. This will make it possible to increase the productivity of the process when using a modern mechatronic control system.

To achieve the goal, the following tasks were set:

- to establish the influence of surfacing parameters on the width of the surfaced bead;
- to establish the influence of surfacing parameters on the height of the surfaced bead;
- to investigate the influence of surfacing parameters on the penetration depth of the base metal.

4. The study materials and methods

The object of our study is the geometric dimensions of the surfaced weld bead. The subject of the study is the formation of the surfaced bead using mechanical low-frequency harmonic oscillations.

Research hypothesis assumes that controlled oscillations of the liquid weld pool make it possible to increase the surfacing productivity by controlling the geometry of the weld bead.

When building a mathematical model, the following assumptions were adopted. Oscillations of the liquid weld pool are considered as harmonic changes with a sinusoidal law. Physicochemical properties of the melt, such as density, viscosity, surface tension, and thermal conductivity, are assumed to be constant within the studied range of modes. The ranges of variation in the oscillation parameters were as follows: frequency $\nu = 2.5\text{--}4.5$ Hz and amplitude $A = 0.004\text{--}0.007$ m. Their choice is justified by previous studies on the resonance characteristics of the "workpiece-liquid pool" system and an analysis of the literature on vibration methods in welding.

Simplifications in the mathematical model include neglecting higher harmonics of weld pool oscillations. The influence of metallurgical reactions in the pool is not taken into account. Consideration is limited to hydrodynamic and thermal processes in the melt.

The ranges of surfacing parameters corresponded to typical operating values for a semi-automatic process. The welding current strength varied within the following limits: $I_s = 100\text{--}200$ A, voltage $U_s = 20\text{--}30$ V, surfacing speed $V_s = 0.3\text{--}0.6$ cm/s.

The surfacing process was carried out at the above-mentioned installation [9], which included a semi-automatic machine PSh 107V (USSR / Ukraine) as a local system for supplying electrode wire and, if necessary, shielding gas. During

surfacing, a welding current source VDU-506 (USSR / Ukraine) was used. A separate mechanism with an adjustable DC electric drive was used to perform welding movement. The movement of the displacement oscillator itself, as well as the entire surfacing cycle, was executed by a control system with a certain programming of its operation.

The geometric parameters of the surfaced beads were determined by experimental and analytical methods. Experimental surfacing was carried out with varying oscillation parameters and process modes, with arc oscillography to control current and voltage. The geometric dimensions of the beads were determined from macrographic cross-sections: height – on an optical microscope, width – by direct instrumental measurement. Regression analysis of experimental data was used to build a mathematical model of the dependence of the geometric dimensions of the bead on surfacing parameters. All measurements of the geometric dimensions of the surfaced beads were carried out in accordance with the requirements from current national standards. DSTU ISO 17639 (study of welded joints – macroscopic and microscopic) and DSTU ISO 17637 (visual and measuring control of welds) were applied. Sheet steel of the St3sp grade was used as the base metal, and solid wire of the ER70S-6 brand was used as the electrode wire.

5. Results of investigating the influence of oscillations on the geometry of the surfaced bead

5.1. Determining the influence of surfacing parameters on a weld bead width

The width of the surfaced bead H was determined based on a mathematical model in the form of an analytical conclusion reported in [10]. This conclusion was drawn based on the fact that the weld bead is formed under conditions of harmonic transverse oscillations of the weld pool due to the influence of an external force

$$F(t) = F_0 \cdot \cos(2 \cdot \pi \cdot \nu \cdot t),$$

where F_0 is the amplitude value of the force; ν is the frequency of oscillations.

The oscillator is schematically shown in Fig. 1. The oscillation of the part being surfaced was carried out by a gearless mechanism with an electric drive based on a stepper motor with precise positioning of the part.

An expression for determining the width of the surfaced bead was derived by solving the equation of forced oscillations of a harmonic oscillator; it takes the following form

$$H = 2 \left| \frac{M_0}{ml \sqrt{(\omega_0^2 - \nu^2)^2 + 4\gamma^2 \nu^2}} \cos(\pi - \theta) \right|, \quad (1)$$

where M_0 is the torque on the stepper motor shaft; m is the mass of the frame where the part to be surfaced is fixed, kg; l is the distance from the axis of oscillation to the center of mass of the melt, which is regulated by the height of the technological substrate (Fig. 1), m; ω_0 is the frequency of natural oscillations of the melt; ν is the frequency of oscillations; γ is the coefficient characterizing the force of viscous friction; θ is the angle between the vector of the forcing effort and the direction of change in coordinate $x(t)$.

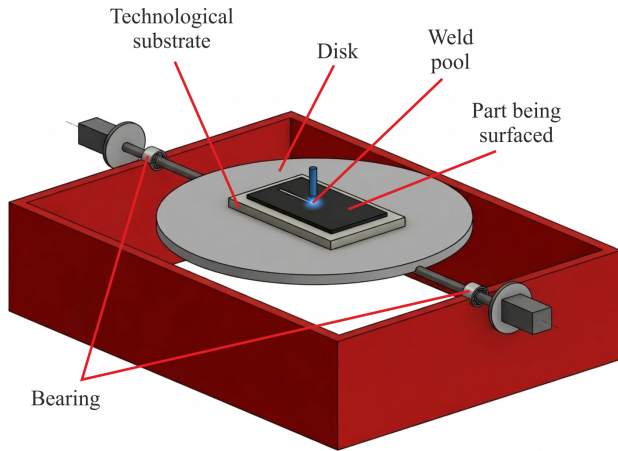


Fig. 1. General oscillator diagram for determining the bead width H according to expression (1)

According to equation (1), by using the Mathcad software package (USA), the width of weld beads was calculated for different values of the surfacing parameters. The results of the calculations are given in Table 1.

Essential and important, especially for users and developers of surfacing technology with controlled pool oscillations, is the assessment of error in the calculated and actual width of the surfaced bead based on the ability to predict the result

that can be obtained from formula (2). The relative error can be determined from the following expression

$$\Delta = \left| \frac{H_{cal} - H_{meas}}{H_{meas}} \right| \cdot 100\%, \tag{2}$$

where H_{cal} is the width value calculated from expression (1); H_{meas} is the width value measured (Table 1).

The total average relative error of this model is 21.7%.

Very important from a practical point of view is the assessment of the influence of each main factor on the formation of weld bead width. This task can be solved in various ways but, in this case, the most simple and effective may be the methodology of average values by Professor Protodyakonov. According to this methodology, the average values of the response – the width of the weld bead for each value of the corresponding main factor are determined. Based on the calculation data, plots for the dependence of average values of a weld bead width on the corresponding factor are constructed.

For example, a number of such plots are shown in Fig. 2. The steeper the resulting plot, the greater the influence of this factor on the formation of width. Analysis of the curves and assessment of the significance of technological factors revealed that the most significant influence on the width of the surfaced bead is exerted by the amplitude of oscillations A . If the curve is horizontal, then this factor does not affect the value of the formation of width at all.

Table 1

Values of bead widths, calculated from equation (1) and measured, with the given relative error

Surfacing current I_s , A	Surfacing speed; V_s , m/s	Oscillation frequency/distance from the axis of oscillation to the center of mass of the melt; ν , Hz/l, mm	Amplitude of oscillations, A , m	Calculated bead width, H_{cal} , mm	Measured bead width, H_{meas} , mm	Relative error, Δ , %
100	0.0061	2.5/270	0.004	10	10.96	8.7
125	0.0072		0.006	16	12.4	29
150	0.005		0.007	19	15.8	20.3
175	0.0039		0.003	7	11.7	41
200	0.0028		0.005	13	15.7	17.2
100	0.0072	3/250	0.005	14	10.3	36
125	0.0039		0.007	19	17.2	10.5
150	0.0061		0.003	8	10.8	26
175	0.0028		0.004	11	15.4	28.6
200	0.005		0.006	18	15.8	14
100	0.0039	3.5/80	0.006	16	13.6	17.7
125	0.0028		0.003	7	13.2	47
150	0.0072		0.004	10	13.8	27.5
175	0.005		0.005	13	14	7
200	0.0061		0.007	20	19	5.2
100	0.0028	4/63	0.007	22	18.8	36.4
125	0.005		0.004	10	11.8	15.3
150	0.0039		0.005	14	14.3	2.1
175	0.0061		0.006	18	14.1	27.7
200	0.0072		0.003	7	11.3	38.1
100	0.005	4.5/60	0.003	8	9.6	17
125	0.0061		0.005	15	18	16.7
150	0.0028		0.006	20	17.9	11.7
200	0.0039		0.004	11	13.8	20.1

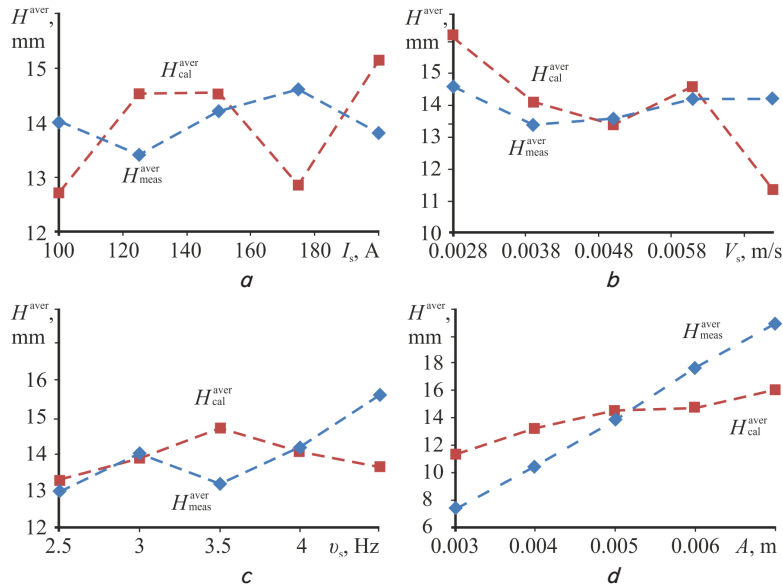


Fig. 2. Plots for the average values of a surfaced bead width, measured H^{aver}_{meas} and calculated H^{aver}_{cal} , determined by the Protodyakonov method: *a* – depending on the surfacing current I_s , A; *b* – depending on the surfacing speed V_s , m/s; *c* – depending on oscillation frequency ν , Hz; *d* – depending on oscillation amplitude A , m

The resulting plots (Fig. 2) demonstrate that at an oscillation frequency in the range of 2.5–4.5 Hz and amplitudes of 0.003–0.007 m, the main influence on the surfaced bead width is the amplitude of the oscillations, namely: with increasing amplitude, the width also increases. Our installation was also used to conduct studies on the influence of oscillations on the liquid metal of the weld pool and the possibility of increasing the weld bead width through its spreading under the angular force of oscillations. The results of the studies showed that the influence of oscillations on the spreading of the metal, which is due to a sufficient value of the inertia force, is observed at frequencies from 10 Hz, while an increase in the amplitude factor contributes to an increase in the width, and an increase in the frequency factor to a decrease.

Table 2 gives results from comparative experimental studies to determine the real values of the width and height of the surfaced bead with and without oscillations of the pool. The quality of bead formation was assessed according to DSTU ISO 17637.

Analyzing the data (Table 2), we can conclude that the presence of oscillations causes a change in the geometry of the surfaced bead. The weld bead width increases and its height decreases. These effects are manifested in two resonant ranges of oscillation frequencies of 2.5–3 Hz and 4–4.5 Hz and retain their character when changing the main parameters of the surfacing parameters within the considered limits.

Table 2

Comparative experimental data on bead width and height

Experiment No.	Current, A	Speed, m/s	Amplitude, m	Frequency, Hz	Width, mm	Height, mm	Bead forming quality
1*	100	0.0028	–	–	10.32	4.18	good
1	100	0.0028	0.007	4	18.8	2.7	satisfactory
2	100	0.0039	0.006	3.5	13.6	2.8	satisfactory
3	100	0.005	0.003	4.5	9.6	4.04	good
4	100	0.0061	0.004	2.5	10.96	3.02	satisfactory
5	100	0.0072	0.005	3	10.3	3	unsatisfactory
6	125	0.0028	0.003	3.5	13.2	4.0	good
7*	125	0.0039	–	–	10.8	2.8	good
7	125	0.0039	0.007	3	17.2	3.9	satisfactory
8	125	0.005	0.004	4	11.8	3.5	good
9	125	0.0061	0.005	4.5	18.0	2.9	good
10	125	0.0072	0.006	2.5	12.4	2.5	satisfactory
11	150	0.0028	0.006	4.5	17.9	5.2	good
12	150	0.0039	0.005	4	14.3	4.5	good
13*	150	0.005	–	–	11.9	5.3	satisfactory
13	150	0.005	0.007	2.5	15.8	3.2	satisfactory
14	150	0.0061	0.003	3	10.8	4.0	good
15	150	0.0072	0.004	3.5	13.8	3.0	satisfactory
16	175	0.0028	0.004	3	15.4	4.9	good
17	175	0.0039	0.003	2.5	11.7	5.6	good
18	175	0.005	0.005	3.5	14.0	4.6	good
19*	175	0.0061	–	–	8.8	5.2	satisfactory
19	175	0.0061	0.006	4	14.1	3.8	good
20	175	0.0072	0.007	4.5	9.0	3.7	satisfactory
21	200	0.0028	0.005	2.5	15.7	6.8	satisfactory
22	200	0.0039	0.004	4.5	13.8	6.3	good
23	200	0.005	0.006	3	15.8	4.9	satisfactory
24	200	0.0061	0.007	3.5	19.0	7.4	satisfactory
25*	200	0.0072	–	–	7.8	6.4	good
25	200	0.0072	0.003	4	11.3	4.7	good

Note: data marked * were obtained without pool oscillations.

5. 2. Determining the influence of surfacing parameters on the weld bead height

The influence of the basic surfacing parameters and the parameters of pool oscillations was determined on the basis of a regression model built on the results of experimental studies. The regression model for calculating height *b* of the surfaced bead was constructed using the regression analysis methodology [11]; it takes the following form

$$\begin{aligned}
 b = & 0.00402 + 0.0488 \cdot I_s \cdot V_s - 4.12 \cdot 10^{-5} \cdot I_s \cdot v - \\
 & - 0.0287 \cdot I_s \cdot A - 7.27 \cdot I_s \cdot V_s \cdot A - \\
 & - 0.00162 \cdot I_s \cdot V_s \cdot v + 2.24 \cdot A \cdot v - 44.8 \cdot A \cdot v \cdot V_s + \\
 & + 7.59 \cdot I_s \cdot A^2 + 1.10 \cdot 10^5 \cdot A \cdot V_s^2 + 0.0725 \cdot V_s \cdot v^2 - \\
 & - 0.263 \cdot A \cdot v^2 + 1.85 \cdot 10^{-7} \cdot I_s^2 \cdot v - \\
 & - 7.70 \cdot 10^{-5} \cdot I_s^2 \cdot V_s - 807 \cdot A^2 - 544 \cdot V_s^2.
 \end{aligned}
 \tag{3}$$

The regression model built captures 94.0% of the total variation in a weld bead height (coefficient of determination $R^2 \approx 0.94$). The adjusted coefficient of determination $\bar{R}^2 \approx 0.92$, that takes into account the number of predictors in the model confirms its statistical adequacy. Based on the regression model equation, contour plots were constructed for surfacing currents in the range of 100–200 A and different values of surfacing speed and liquid pool oscillations. From the analysis of the resulting contour plots for the formation of the weld bead height, some of which are shown in Fig. 3, it follows that the minimum value of the height is formed in two frequency ranges. This pattern is observed within the frequencies $v = 2.5\text{--}3$ Hz and $v = 4\text{--}4.5$ Hz at any current strength and surfacing speed. But the minimum value of weld bead height *b*, or close to it, can be obtained in two frequency ranges under one technological mode. These modes are the following:

- at $I_s = 125$ A, $V_s = 0.0028$ m/s;
- at $I_s = 150$ A, $V_s = 0.0039$ m/s, $V_s = 0.005$ m/s and $V_s = 0.0072$ m/s;
- at $I_s = 175$ A, $V_s = 0.0028$ m/s, $V_s = 0.0039$ m/s;
- at $I_s = 200$ A, $V_s = 0.0072$ m/s.

In other words, the minimum value of weld bead height is always formed in the frequency ranges of 2.5–3 Hz and 4–4.5 Hz. It should also be noted that the ratio of the current strength and surfacing speed determines the amplitude value and the possibility of forming the minimum value of weld bead height in two frequency ranges under one technological mode. The most effective is the amplitude range $A = 0.004\text{--}0.006$ m.

A comparison of the weld bead heights obtained without oscillation (Table 2, Fig. 3) with the minimum height of the weld bead formed under a similar technological conditions using the oscillation of the weld pool is given below. At the surfacing current strength without oscillations $I_s = 100$ A and $V_s = 0.0028$ m/s, the minimum height of the surfaced bead is $b_{min} = 4.18$ mm. The minimum value with oscillations under this processing conditions is achieved at a frequency of $v = 2.5$ Hz and an amplitude of $A = 0.007$ m and does not exceed $b_{min}^{osc} = 0.7$ mm (Fig. 3, a). That is, the size of the height of the bead due to oscillations decreased by at least 6 times. At a current of $I_s = 125$ A and a surfacing speed of $V_s = 0.0039$ m/s, the height of the bead is $b_{min} = 2.8$ mm without oscillations. The minimum value with oscillations under this technological conditions is observed at $v = 2.5$ Hz and $A = 0.005\text{--}0.007$ m and is $b_{min}^{osc} = 2.3$ mm. The size of the height of the bead due to oscillations decreased by 1.2 times. At $I_s = 150$ A and $V_s = 0.005$ m/s, the height of the surfaced

bead is $b_{min} = 5.3$ mm without oscillations. With oscillations, at $v = 2.5$ Hz, $A = 0.004\text{--}0.006$ m, the minimum height value is $b_{min}^{osc} = 2.7$ mm (Fig. 3, a). That is, the height of the bead due to oscillations decreased by 2 times. At a welding current strength without oscillations $I_s = 175$ A and a speed $V_s = 0.0061$ m/s, the height of the bead is $b_{min} = 5.2$ mm. Under this technological mode, the minimum height of the surfaced bead is $b_{min}^{osc} = 2$ mm at oscillations with a frequency of $v = 2.5$ Hz and an amplitude of $A = 0.004\text{--}0.006$ m. The height of the bead due to oscillations decreased by 2.6 times. Under modes without oscillations $I_s = 200$ A, $V_s = 0.0072$ m/s, the height is $b_{min} = 6.4$ mm. The minimum value with oscillations is observed at the oscillation frequency $v = 2.5$ Hz and their amplitude $A = 0.004\text{--}0.006$ m and is $b_{min}^{osc} = 1$ mm (Fig. 3, c). The height of the bead, under these modes, decreased by 6.4 times due to oscillations.

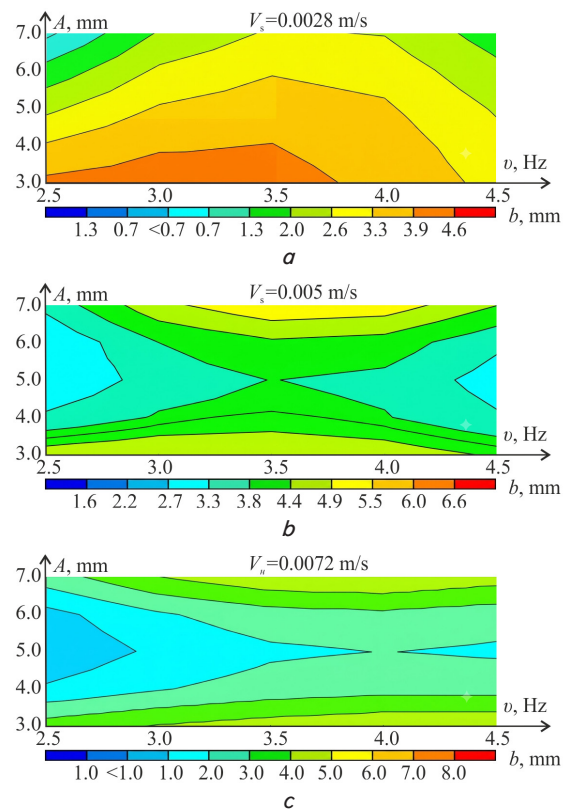


Fig. 3. Plots for the formation of surfaced bead height *b* under the following modes: a - $I_s = 100$ A, $V_s = 0.0028$ m/s; b - $I_s = 150$ A, $V_s = 0.005$ m/s; c - $I_s = 200$ A, $V_s = 0.0072$ m/s

Therefore, the value of a surfaced bead height can be reduced by approximately 1.2–6.4 times using harmonic transverse oscillations of the weld pool.

5. 3. Determining the influence of surfacing parameters on the depth of base metal penetration

The depth of penetration was determined for the beads obtained under separate technological modes, both with and without oscillations of the pool. The technological modes and oscillation regimes of the pool at experimental surfacing are given in Table 3.

Macrographic cross-sections of samples for studying the influence of pool oscillation parameters on penetration depth are shown in Fig. 4. Fig. 5 depicts a diagram of the results

from determining a penetration depth of the base metal depending on the selected pool oscillation parameters and surfacing parameters in comparison with the same modes without oscillations.

Table 3

Technological modes and pool oscillation regimes at experimental surfacing to determine penetration depth

Experiment number	Surfacing current, A	Surfacing speed, m/s	Oscillation frequency, Hz	Amplitude of oscillations, m
1*	100	0.0028	–	–
1			4	0.007
2*	125	0.0039	–	–
2			3	0.007
3*	150	0.005	–	–
3			2.5	0.007
4*	175	0.0061	–	–
4			4	0.006
5*	200	0.0072	–	–
5			4	0.003

Note: Experiments marked * were performed without pool oscillations.

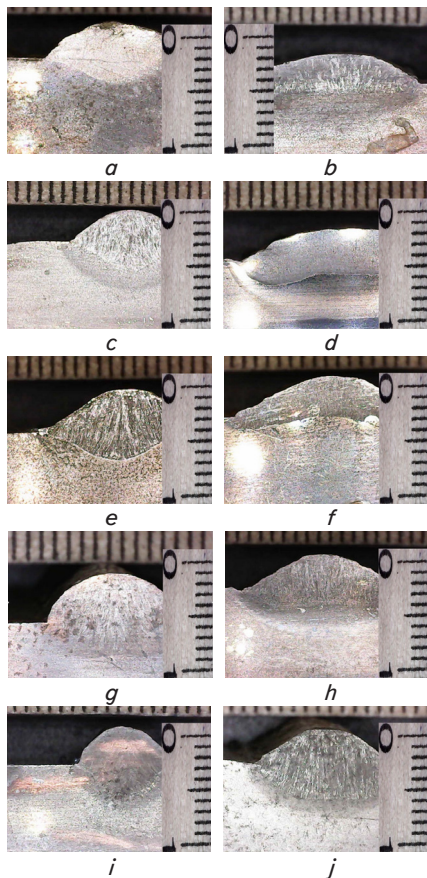


Fig. 4. Macrographic cross-sections of the surfaced beads, both under the action of liquid pool oscillations (*b, d, f, h, j*) and without oscillations (*a, c, e, g, i*) in accordance with Table 3: *a* – experiment number 1*; *b* – experiment number 1; *c* – experiment number 2*; *d* – experiment number 2; *e* – experiment number 3*; *f* – experiment number 3; *g* – experiment number 4*; *h* – experiment number 4; *i* – experiment number 5*; *j* – experiment number 5

Our analysis of the results revealed that the penetration depth of the beads obtained without pool oscillations is within 2–3 mm, and of the beads obtained using pool oscillations – 1–3 mm.

The greatest decrease in the penetration depth under the action of the oscillatory motion of the pool at the level of 1.0–1.5 mm is recorded under the surfacing parameters with a current of 100–150 A. With a further increase in the surfacing current, the penetration depth approaches the value of the depth obtained without oscillations.

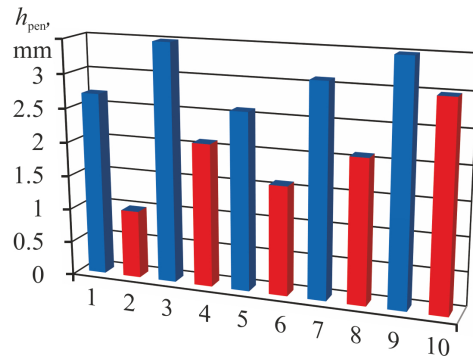


Fig. 5. Comparative diagram for determining penetration depth h_{pen} (mm) under technological modes in Table 3: 1 – experiment number 1*; 2 – experiment number 1; 3 – experiment number 2*; 4 – experiment number 2; 5 – experiment number 3*; 6 – experiment number 3; 7 – experiment number 4*; 8 – experiment number 4; 9 – experiment number 5*; 10 – experiment number 5

The critical factor influencing the geometric parameters of a weld bead is the dispersion of the welding arc, which accompanies the surfacing process with fluctuations of the weld pool.

6. Discussion of results based on studying the influence of surfacing parameters on the geometry of a surfaced bead

Our analysis of the experimental and theoretical data reported in this work confirms that controlled low-frequency harmonic oscillations of the weld pool are an effective tool for targeted control over the geometry of a surfaced bead. Unlike conventional control methods (changing the current, speed, arc voltage), oscillations directly affect the hydrodynamics of the liquid melt, changing the distribution of heat flows and the nature of crystallization [2, 4].

It was experimentally established in our work (Table 2) that oscillations lead to a complex change in the geometry of a weld bead: an increase in its width, a sharp decrease in height (up to 6 times), and a decrease in the penetration depth. These effects are manifested in two resonant frequency ranges of 2.5–3 Hz and 4–4.5 Hz and are preserved when the main surfacing parameters change. The results are consistent with the ideas of forced oscillations of the liquid layer and complement existing studies on oscillation welding and surfacing [12].

In this work, oscillations are considered as an independent technological parameter, which corresponds to modern trends in the development of mechatronic and adaptive welding systems [13].

The mathematical model built, based on the equation of forced oscillations, makes it possible to predict a change in the weld bead width depending on the amplitude and frequency of excitation. The average relative error of the model is 21.7% (Table 1), which is acceptable for highly nonlinear welding processes. The model correctly describes the general nature of width change and reveals resonant zones. At the same time, it has a tendency to overestimate the width at high frequencies and underestimate it at low frequencies. Comparison with literature data shows that the achieved accuracy is comparable to the results from similar regression models for predicting the geometry of a weld bead in arc welding of steels, in which the average relative error of prediction is 11–25% [14].

The increase in the surfaced bead width is due to the action of interrelated mechanisms:

- inertial forces that cause transverse redistribution of the melt;
- a decrease in local heat concentration due to a decrease in the time of arc exposure to one point;
- an increase in turbulization and circulation of the melt, which facilitates its spreading;
- a decrease in capillary forces and surface tension gradients during oscillatory motion [15–18].

As a result, the pool acquires a flatter and wider shape. This is confirmed by both experimental measurements (Table 2) and macrographic data (Fig. 4). Analysis of experimental dependences revealed that the main factor determining the weld bead width is the amplitude of oscillations. An increase in the amplitude leads to an increase in the width by 1.5–2 times. The frequency of oscillations has a non-monotonic effect: the maximum expansion is observed in the range of 2.5–4.5 Hz, while at frequencies above 10 Hz the effect weakens.

The welding current and the surfacing rate retain their conventional influence. An increase in the current contributes to an increase in the width, an increase in the rate, on the contrary, to its decrease (Table 2). However, the amplitude of oscillations can have a comparable or stronger effect on the geometric dimensions of the surfaced bead [18, 19].

The identified resonance ranges (2.5–3 and 4–4.5 Hz) correspond to the natural frequencies of the weld pool oscillations and are consistent with the theoretical and experimental data reported by other authors [20, 21]. In these zones, the amplitude of the melt response is maximum, which leads to the greatest expansion of the weld bead.

The regression model built (3) demonstrates a high sensitivity of the weld bead height to the amplitude and frequency of oscillations. The minimum height values are stably achieved in the same resonance ranges as the maximum width. The height prediction error does not exceed 15%, which confirms the practical applicability of the model.

The decrease in the weld bead height is explained by the accelerated spreading of the metal across the width, the decrease in the volume of the melt in the central zone, and the redistribution of thermal energy. The oscillations contribute to the smoothing of surface waves and the formation of a more uniform profile of the surfaced layer, similar to the effects known in the oscillation treatment of cast and welded products.

The greatest decrease in height is observed at frequencies of 2.5–3 and 4–4.5 Hz (Table 2), which further confirms the resonant nature of the process. Under these conditions, the internal circulation of the melt is enhanced, and the local heat concentration is reduced, which leads to the formation of a flatter bead.

The depth of penetration is a critically important parameter that determines the degree of mixing of the base and surfaced metal. Experiments have shown (Fig. 5) that the introduction of oscillations leads to a decrease in the penetration depth by 0.5–1.5 mm at currents of 100–150 A. At higher currents (175–200 A), the effect of oscillations is weakened, and the depth approaches the values characteristic of surfacing without oscillations. This is consistent with the results of studies on oscillation welding, in which the decrease in depth is explained by a decrease in heat concentration and a change in the shape of the arc [15, 17]. At moderate currents, mechanical heat redistribution plays a significant role, while at high currents the thermal power of the arc dominates, which compensates for the effect of oscillations. The observed nonlinearity corresponds to the idea of the "thermal saturation" of the weld pool. Oscillations enhance horizontal melt flows, reduce the stability of the central high-temperature core, and weaken Marangoni convection. As a result, the vertical direction of heat flows decreases and the penetration depth decreases. An additional role is played by the expansion of the arc base and a more uniform distribution of heat across the width of the bead.

The most pronounced decrease in the penetration depth is achieved at amplitudes of 0.004–0.007 m and frequencies of 2.5–4.5 Hz (Table 3, Fig. 4). For oscillation frequencies above 10 Hz, the system does not have time to respond to excitation, and the effect decreases. Oscillations lead to redistribution of heat flows and intensification of melt hydrodynamics. A decrease in local heat concentration is accompanied by an expansion of the heating zone and the formation of a flatter pool. Forced oscillations cause a resonant response of the liquid metal, which explains the appearance of stable frequency ranges of the maximum effect. A more uniform surfaced layer with an increased width, reduced height and penetration depth is formed. Compared with conventional geometry control methods, this approach provides higher accuracy and dynamic control [8].

The increase in surfacing productivity is directly related to the established change in the geometry of the bead. Increasing the width of the bead by 1.5–2 times reduces the number of runs required to cover a given surface by the corresponding multiple. According to the measurement results, at a current strength of 100 A and a surfacing speed of 0.0028 m/s, the width of the bead without oscillations was 10.32 mm. The introduction of oscillations with a frequency of 4 Hz and an amplitude of 0.007 m in the same modes led to an increase in the width to 18.8 mm. A similar trend was observed throughout the studied range of currents 100–200 A (Table 2). Reducing the number of runs proportionally reduces the total process time and electrode wire consumption.

The reduction in the height of the bead is even more significant: the height decreases by 1.2–6.4 times depending on the processing conditions (Table 2, Fig. 3). At a current of 200 A and a speed of 0.0072 m/s, the height of the bead without oscillations was 6.4 mm. Under the action of oscillations of 2.5 Hz with an amplitude of 0.004–0.006 m, its value decreased to 1 mm. Reducing the height of the bead directly reduces the allowance for further machining. This is accompanied by a decrease in cutting tool wear and a reduction in energy costs for finishing operations. The third factor in increasing productivity is a decrease in the penetration depth by 0.5–1.5 mm at currents of 100–150 A (Fig. 5). Reducing the proportion of the base metal in the surfaced layer ensures the achievement of the specified chemical composition and surface properties with a smaller number of surfacing layers.

This further reduces the consumption of electrode wire and the overall process time.

The practical significance of our results relates to the possibility of increasing the productivity of surfacing by increasing the width of the bead and reducing the number of runs. Due to a significant reduction in height, the amount of necessary further machining, metal consumption, and energy costs are reduced. Reducing the depth of penetration reduces the degree of mixing of the main and filler materials. This reduces the likelihood of the formation of unfavorable structures, which has a positive effect on the operational properties of the restored parts. These effects, increased bead width, smaller height, and depth of penetration meet the typical requirements for the restoration surfacing of large-sized parts with extended working surfaces.

The proposed method is promising for several industries with extended working surfaces of parts. In transport engineering, this is the restoration of shafts and wheelsets where the uniformity of the layer along the length is important. In the energy sector, these are generator shafts and turbine elements, where it is critical to preserve the properties of the base metal due to the reduced penetration depth. In agricultural engineering, this is strengthening the working bodies of plows, plowshares, and cultivator bodies with wear-resistant layers. In mining and metallurgical equipment, this is the restoration of rolling mill rolls, mill armor, and crushers, where high surfacing productivity is required.

Controlled harmonic oscillations are an effective means of complex control over the geometry of the surfaced bead. Two stable resonant frequency ranges (2.5–3 and 4–4.5 Hz) were identified, at which the maximum increase in width, a significant decrease in height and a decrease in the depth of penetration are achieved. The amplitude of oscillations is the main control parameter. Our results are consistent with world research and confirm the high industrial prospects of the oscillation-controlled surfacing method.

The results of the study were obtained in limited ranges of currents, speeds, amplitudes, and frequencies. They apply to surfacing on massive flat samples. As a drawback of the work, it can be noted that modes with high heat input, thin-walled parts, and other welding processes (Tungsten Inert Gas, Submerged Arc Welding, welding with pulsed modes) were not considered. In addition, a single-frequency oscillation excitation system in one plane was used, which limits the generalization of the results.

Promising directions for further development of this research are the use of numerical modeling of pool hydrodynamics (Computational Fluid Dynamics + Finite Element Method), the study of high-frequency and multi-plane oscillations. Also of interest is the design of adaptive control systems with feedback and the study of the influence of oscillations on the microstructure and properties of surfaced metal. Of particular interest are industrial tests on real parts. All this requires additional experimental studies with the simultaneous design of new equipment that would allow for high-frequency and/or multi-plane oscillations during surfacing. It is also necessary to refine the mathematical model, which should take into account oscillations with a higher frequency and/or directed in different planes.

7. Conclusions

1. We have experimentally established that controlled low-frequency oscillations of the weld pool increase the sur-

facied bead width by 1.5–2 times compared to the surfacing without oscillations. The determining parameter is the amplitude of the oscillation (in the range of 0.004–0.007 m), while the frequency affects non-monotonically: the maximum expansion is achieved in the resonance zones of 2.5–3 and 4–4.5 Hz. The mathematical model, which we built based on the equation of forced oscillations, predicts a change in the width with an average relative error of 21.7%, which is acceptable for highly nonlinear welding processes.

2. The introduction of oscillations leads to a decrease in the surfaced bead height by up to 6 times, which is due to the accelerated spreading of the metal across the width, the redistribution of thermal energy, and the enhancement of the internal circulation of the melt. The minimum height values are achieved in the same resonant frequency regions as the maximum width. The error of the regression model for predicting the height does not exceed 15 %, which confirms its practical applicability.

3. The use of oscillations reduces the depth of penetration of the base metal by 0.5–1.5 mm within the current range of 100–150 A. The decrease is explained by the weakening of the vertical direction of heat flows, the reduction of local heat concentration, and the intensification of horizontal hydrodynamic flows of the melt. At currents of 175–200 A, the effect is weakened due to the dominance of the thermal power of the arc, which corresponds to the phenomenon of "thermal saturation" of the weld pool.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Volodymyr Lebediev: Conceptualization, Methodology, Writing – original draft, Supervision; **Sergii Novykov:** Conceptualization, Methodology, Investigation, Writing – original draft; **Serhii Loi:** Validation, Investigation, Writing – review & editing, Visualization; **Volodymyr Spiharenko:** Validation, Investigation, Writing – review & editing, Visualization; **Maksym Matviienko:** Validation, Formal analysis, investigation, Writing – review & editing, Visualization.

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