Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2022, № 2 (106) https://doi.org/10.33108/visnyk_tntu2022.02
*ISSN 2522-4433. Web: **visnyk.tntu.edu.ua***

UDC 621.791.03

SOME FEATURES OF AUTOMATIC ELECTRIC ARC SURFACING UNDER THE FLUX WITH CONTROLLED PERIODIC CHANGE OF MODES

Volodymyr Lebedev[1]; Victor Tyschenko[1]; Sergiy Loy[2]; Oleksiy Khalimovskyy[1]

[1]E. O. Paton Electric Welding Institute of National Academy of Sciences of Ukraine, Kyiv, Ukraine
[2]National University of Shipbuilding, Mykolayiv, Ukraine

Summary. *The development and application of automatic electric arc surfacing under flux with controlled periodic change of modes makes it possible to expand significantly the possibilities of traditional technological processes of surfacing. The carried out experimental investigations make enabled us to determine the advantages of the welding process with modulation of modes in comparison with welding in stationary mode. It is established that the parameters of the modulated welding current (frequency, sparseness) determine the degree of influence on the physical and mechanical characteristics of the welded metal and in most cases improve them compared to the characteristics of stationary mode. The result of the analysis defines that in the pulse mode it is possible to achieve the reduction of inclusions from the composition of the flux by almost 30%. This reduction is an additional factor in ensuring the characteristics of strength (hardness, wear resistance) of the weld roller and weld.*
Key words: *electric arc, automatic surfacing, melting electrode, pulse mode, flux, sparseness.*

https://doi.org/10.33108/visnyk_tntu2022.02.101 *Received 11.03.2022*

Statement of the problem. Electric arc welding, restoration and strengthening by the methods of additive technologies of units, parts of machines, as well as mechanisms of various purposes and fields of application are now of great importance. This is due to good results of products quality assessment obtained during welding and surfacing in general, and under flux in particular. The results of electric arc surfacing under the flux can be improved both by the use of new active and protective materials, and the use of new processes implemented due to technical means. Therefore, the investigation of the effect of periodic changes in the operation modes of the automatic electric arc welding process on the physical and mechanical properties of the structure of the deposited metal and the fusion zone with the base metal is very important.

Analysis of the available investigation results.

Processes with pulsed and modulated algorithms for the operation of welding current source, as well as electrode wire supply systems, are considered in papers [1, 2, 3]. The effectiveness of such systems application is described in papers [4, 5, 6, 7] and in many other materials. At the same time, it should be noted that surfacing with the use of low-frequency modulation is quite effective in terms of a number of technical, technological and economic indicators of the equipment used, as well as during the execution of a large number of both single and continuous operations.

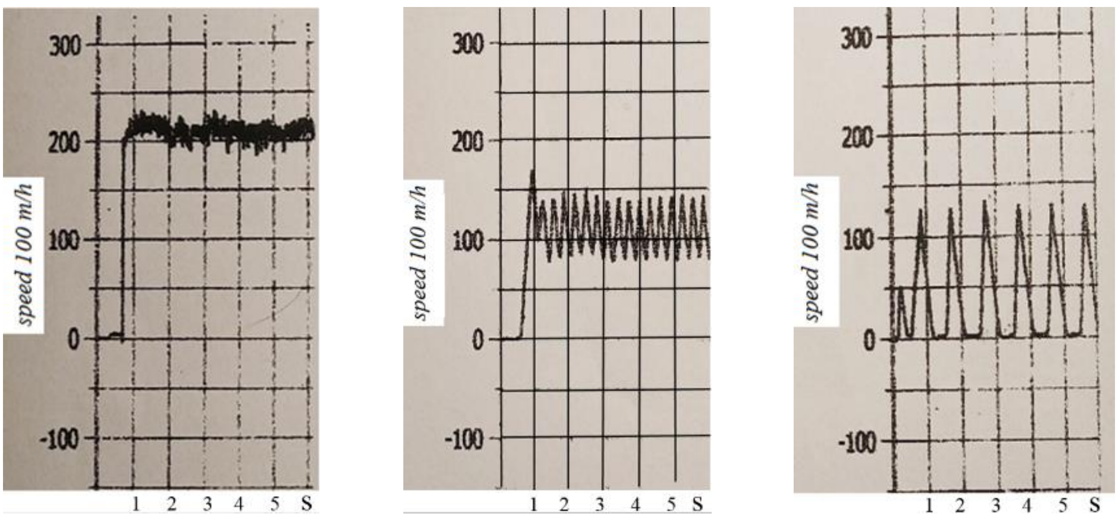
Existing investigations of the technological features of modulated actions application, indicated in papers [8, 9, 10] and other materials, do not allow to identify regularities for obtaining generalizations of their application in various production conditions during welding and surfacing of ship equipment, agricultural machinery units, metallurgical equipment, tools, particularly, stamping tool.

Corresponding author: Oleksiy Khalimovskyy; e-mail: o.khalimovskyy@ukr.net

Objective of the investigation. The objective of this investigation is further experimental research of the structure of the deposited metal and the fusion zone with the base metal in order to identify the peculiarities of their formation during the periodic change of modes in the process of deposition under the flux layer, as well as the search and determination of parameters for such modes in order to improve the quality indicators of the deposited layer.

Statement of the problem. There is a number of disadvantages in the process of welding under flux, which are the increase of non-metallic inclusions, decrease in the quality of the deposited layer in the fusion area with the base metal, and the difficulty of performing the process under conditions of the difference between the surfaces levels which are to be deposited. This results in the search of new solutions for improving the technique and technology of welding-surfacing. It is well known that one of the methods of improving the weld quality is the application of welding technology with mode modulation. In order to choose the modulation mode, which makes it possible to improve physical and mechanical properties of the deposited layer, it is necessary to carry out systematic investigations of the influence of modulation parameters on the metal characteristics in the welding area.

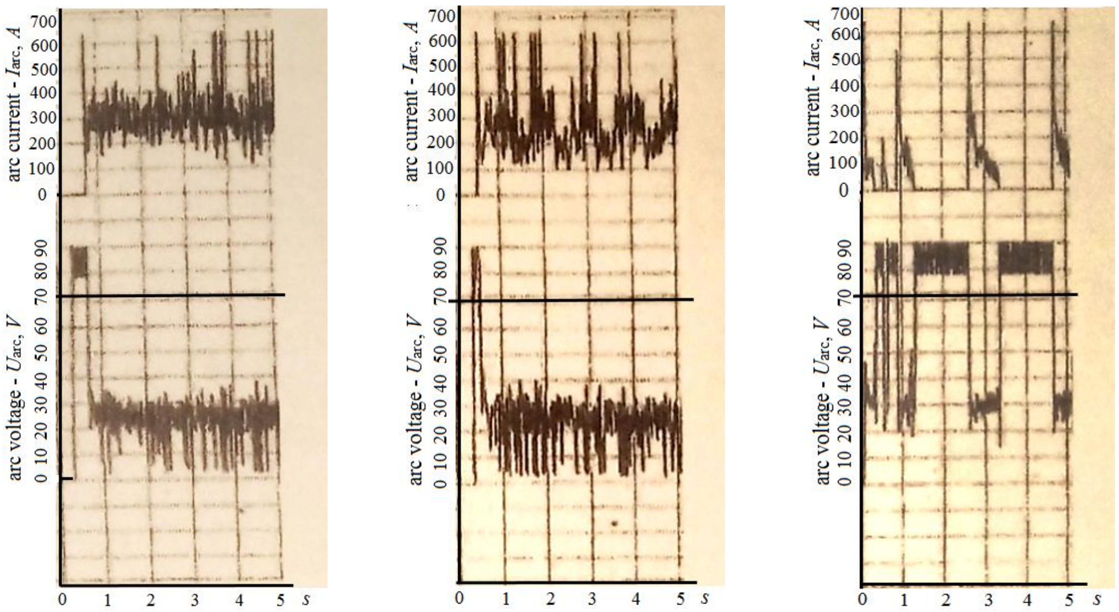
Investigation of the peculiarities of automatic electric arc surfacing under the flux with controlled periodic change of modes. The formation of dynamic modes of specific welding and surfacing machine depends on its ability to work out modulation frequencies, as well as such parameters as the duration of the pulse t_{pt} and pause t_p. Direct current electric motors used in electrode wire feeding systems of conventional welding equipment – semi-automatic and automatic machines – have limited dynamic capabilities. The cycle of experimental investigations was carried out using conventional welding and surfacing equipment – automatic machine A-874N with rectifier VDU-506. The set of this equipment was additionally equipped with prefix developed earlier – OI-10 modulator [11] and universal computerized system for controlling the supply of the electrode wire [12] designed by Paton IEW which provided modulated mode of the surfacing process. The functional capabilities of the electrode wire feed control system made it possible to set and change the modulation parameters very accurately, as well as to provide visualization of all the modulation parameters both in the task mode and during the welding-surfacing process. The oscillograms of the speed of the electrode wire in different modes for controlling the frequency of rotation of the drive motor shaft, obtained due to special recording device based on tachogenerator in 5-second cycle are shown in Fig. 1.



a b c

Figure 1. Electrode wire feeding speed: a – stationary mode;
b – modulated mode: t_{pt} –0.15 c;t_p–0.15 c; c – modulated mode: t_{pt}– 0,1 c; t_p– 0,8 c

Four-roller mechanism based on direct current electric motor of SL 661 type was used for feeding. It can be seen that there are certain limitations while organizing the modulated mode with frequencies with 3.5 Hz order (Fig. 1 b). Modulation frequencies of 1–2 Hz are worked out quite well. All this is confirmed by the results of the measurements of current I_{arc} and arc voltage U_{arc}. The examples of characteristic current and voltage oscillograms for certain surfacing modes are presented in Fig 2.



a b c

Figure 2. Oscillograms of the surfacing process with current modulation due to the change in frequency of the drive motor shaft rotation: a – stationary arc, I_{arc} – 290 *A*, arc voltage U_{arc} – 25 *V*, welding speed – $V_{w.sp}$ =10.5 m/h, overhang of electrode wire *L*=0.02 m; b – modulated current: I_{arc} – 290 *A*, U_{arc} – 25 *V*, $V_{w.sp}$ =10.5 m/h, *L*=0.02 m; t_{pt}=0.7 s; t_p =0.3 s; c – modulated current: I_{arc} – 120 *A*, U_{arc} – 29 *V*, $V_{w.sp}$ =10.5 m/h, *L*=0.02 m; t_{pt} =0.2 s; t_p=1.3 s

It is evident from the oscillograms that the surfacing process can be controlled with the frequencies which do not exceed 1.0–2.0 Hz. It should be taken into account that the range of realized frequencies during mode modulation to a great extend depends on the ratio of maximum and minimum feeding speed of the electrode wire, as well as on maximum feeding speed.

The modulator block can be mounted: in the automatic control system A1416; in the source of welding current VDU1201 or VZH1600; in other designs of welding equipment, which have initial parameters that meet the requirements of performing the experimental work.

The results were compared while performing welding-surfacing at the average value of direct current (stationary mode), as well as welding at pulsating current value (modulated mode).

Assessment of the seams quality was carried out by:

a) external examination with the detection of drips, surface irregularities, etc.;

b) investigation of macro-grinds with the determination of the penetration depth, the seam width, the reinforcement height, as well as the presence of pores and cracks;

c) according to the result of the analysis of metal microstructures and the areas of thermal influence;

d) comparison of chemical composition;

e) conduction of a set of tests related to a number of basic mechanical properties of the weld metal.

During the experiments, the voltage and current were fixed by the magnitude and duration of pulses (the upper value of the welding current value) and the pause (the lower value of the current and the upper value of the voltage value).
Submerged welding investigations for modulated modes were carried out using:

- samples from steels 09G2 (low-carbon structural steel) and VSt3ps (carbon structural steel) up to 40 mm thick as welding or surfacing materials;
- SV-08 electrode wire (for automatic flux-cored welding) with diameters up to 4.0 mm;
- welding flux AN-348A (intended for mechanized welding and surfacing of structures made of carbon non-alloyed and low-alloyed steels with welding wire brands SV-08, etc.).

Among the variety of existing regularities of the process of electric arc welding under flux (strength, geometric dimensions), we investigate the dependence of chemical composition of the weld metal on the parameters of the modulated welding mode. The experiment plan and the method of information processing were adopted similarly to those described in paper [13].

In order to obtain this dependence, the data of the modes presented in Table 1 were used, as well as the comparative average results of measurements of metal chemical composition given in Table 2.

Table 1

Parameters of automatic welding-surfacing under flux

Parameters of surfacing							
Sample number	t_{pt}, s	t_p, s	f, Hz	I_{pt}, A	I_p, A	U_{arc}, V	$V_{w.sp}$, m/h
1	0.1	0.1	5	800	500	38	21.5
2	0.2	0.2	2.5	800	500	38	21.5
3	0.3	0.3	1.7	800	500	38	21.5
4	0.4	0.4	1.25	800	500	38	21.5
5	0.5	0.5	1	800	500	38	21.5
6	0.6	0.6	0.8	800	500	38	21.5
7	0.2	0.1	3.3	800	500	38	21.5
8	0.3	0.1	2.5	800	500	38	21.5
9	0.4	0.1	2	800	500	38	21.5
10	0.5	0.1	1.7	800	500	38	21.5
11	0.6	0.1	1.4	800	500	38	21.5
12	0.7	0.1	1.25	800	500	38	21.5
13	0.1	0.9	1	800	500	38	21.5
14	0.1	0.8	1.1	800	500	38	21.5
15	0.1	0.7	1.25	800	500	38	21.5
16	0.1	0.6	1.4	800	500	38	21.5
17	0.1	0.5	1.7	800	500	38	21.5
18	0.1	0.4	2	800	500	38	21.5
19	0.1	0.4	2	800	500	38	21.5

Table 2

Chemical composition of the seam metal during submerged arc welding

Sample	Chemical composition, %		
	C	Si	Mn
Wire	0.08	0.92	1.7
Base metal	0.08	0.32	1.55
1	0.06	0.92	2.0
2	0.06	0.32	2.05
3	0.06	0.6	1.9
4	0.06	0.42	2.05
5	0.06	0.32	2.05
6	0.06	0.34	1.7
7	0.06	0.36	1.7
8	0.06	0.25	1.8
9	0.06	0.38	1.7
10	0.07	0.40	1.7
11	0.065	0.41	1.65
12	0.09	0.43	1.78
13	0.09	0.55	1.72
14	0.13	04	1.75
15	0.08	0.53	1.73
16	0.09	0.53	1.78
17	0.10	0.57	1.8
18	0.09	0.57	1.8
19	0.09	0.57	1.8

The chemical composition was measured by optical emission spectroscopy.

Dependencies of the content of carbon $C = \psi(f)$, silicon $Si = \psi(f)$, manganese $Mn = \psi(f)$ on the frequency of the welding current modulation are obtained in the form of regression equations

$$C = 0{,}07 + 0{,}00157x_1 + 0{,}00157x_2 - 0{,}022x_3 - 0{,}0037x_4, \quad (1)$$

$$Si = 0{,}377 + 0{,}01x_1 + 0{,}0244x_2 - 0{,}003x_3 - 0{,}0005x_4, \quad (2)$$

$$Mn = 1{,}591 + 0{,}2347x_1 + 0{,}0576x_2 - 1{,}78x_3 - 0{,}278x_4, \quad (3)$$

where: x_1, x_2 – duration of the pulse and pause, respectively; x_3, x_4 – current in pulse and pause, respectively.

The graphs of functions of the investigated dependencies taking into account equations (1), (2), (3) are presented in Fig. 3, Fig. 4, Fig. 5.

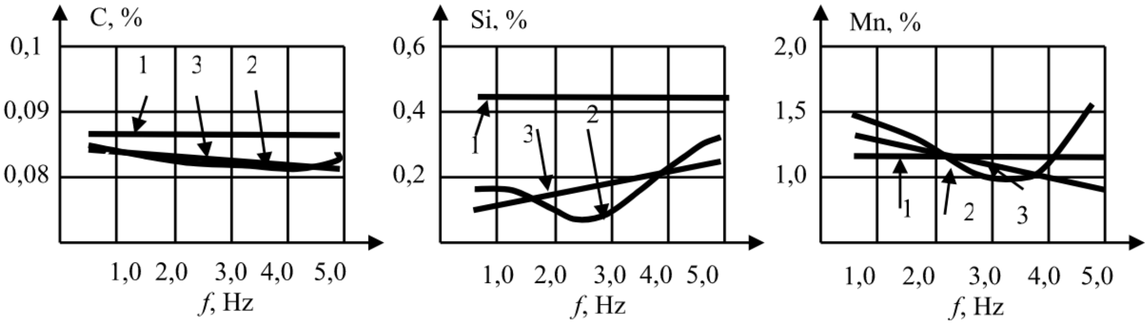


Figure 3. Dependences of carbon, silicon and manganese content on the modulation frequency at $t_{pt} = t_p$ (samples 1–6) during welding: 1 – stationary arc, 2 – arc with modulation; 3 – approximation of mode data 2

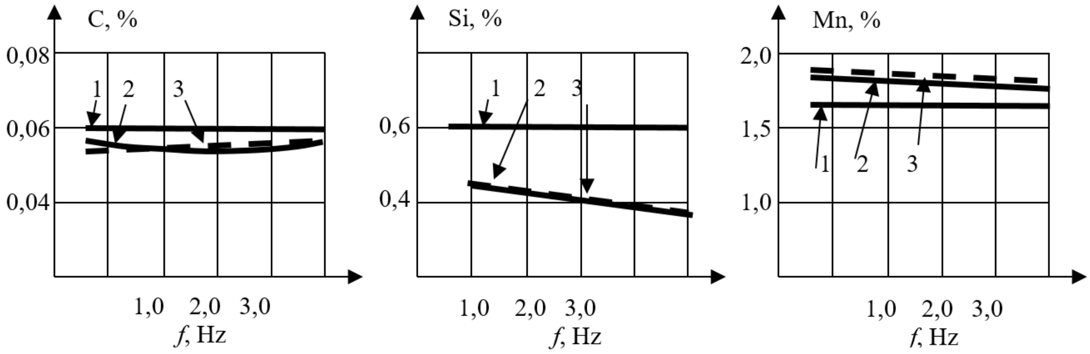


Figure 4. Dependences of carbon, silicon and manganese content on the modulation frequency at $t_{pt} < t_p$ (samples 7–12) during welding: 1 – stationary arc, 2 – with modulation; 3 – approximation of mode data 2

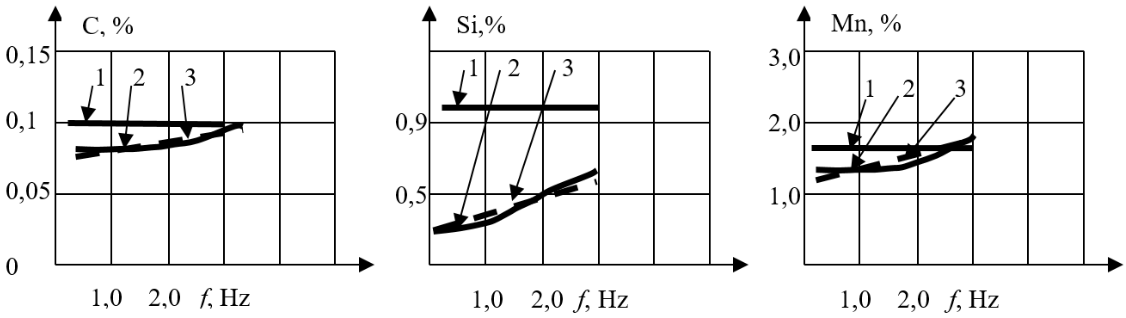


Figure 5. Dependences of carbon, silicon and manganese content on the modulation frequency at $t_{pt} > t_p$ (samples 13–19) during welding: 1 – stationary arc, 2 – arc with modulation;
3 – approximation of mode data 2

As a rule, while developing technical and technological recommendations for the application of submerged arc welding with the use of modulated modes in all their diversity for the compilation of technological maps and the selection of welding current modulation modes, as a rule, the presence of predictive results is required. A simplified definition of the necessary (most effective) modes for improving the quality of automatic flux-cored welding with controlled mode of periodic changes in the welding current can be presented in the form of equations of segments of direct dependences of the percentage content of materials on frequency, shown in the graphs Figs. 3, Fig. 4, Fig. 5.

Based on the above mentioned, for the elements of the chemical composition of the metal we can write:

$$\frac{f - f_1}{f_2 - f_1} = \frac{(C, Si, Mn) - (C_1, Si_1, Mn)}{(C_2, Si_2, Mn) - (C_1, Si_1, Mn)}, \qquad (4)$$

where: f, f_1, f_2 – the value of the process frequency is current, finite along the line segments according to the frequency coordinates; C, C_1, C_2, Si, Si_1, Si_2, Mn, Mn_1, Mn_2 – the current and final values of the chemical composition of the process according to the line segments, respectively according to the coordinate of the chemical components.

At modulation frequencies of 5 Hz and higher, the electrode wire feeding system is unable to work out the set parameters. That is, there is practically no modulation in its entire volume, which is confirmed by the dependences in Fig. 3, Fig. 4, Fig. 5.

It is important to note that other characteristics of the influence of modulated modes can be interpreted on the basis of system measurements using the above-described simple technique. This can be applied, for example, to the geometric dimensions of the welded roller presented in the Table 3.

Table 3

Parameters and shape coefficients of seams

Seam parameters					
Sample number	Width, mm	Depth of melting, mm	Height amplification, mm	Coefficients	
				Of melting	Of amplification
Initial Sample	22	10	5	0.45	0.25
1	21	6	2	0.3	0.15
2	20	6	3	0.3	0.15
3	19	6	3	0.31	0.15
4	18	6	3	0.33	0.16
5	17	7	4	0.4	0.2
6	16	8	4	0.5	0.2
7	21	9	4	0.43	0.2
8	21	8	4	0.38	0.19
9	23	8	4	0.39	0.17
10	20	9	4	0.45	0.2
11	21	7	5	0.33	0.35
12	20	9	5	0.45	0.26
13	12	2	3	0.16	0.25
14	3	3	3.2	0.2	0.28
15	16	4	3	0.25	0.2
16	16	4	3	0.3	0.1
17	17	6	4	0.3	0.2
18	17	6	4	0.3	0.2
19	18	7	4	0.4	0.2

Analyzing the dependences $C=\psi(f)$, $Si=\psi(f)$, $Mn=\psi(f)$ it can be concluded that the most significant effect on the chemical composition is exerted by the relative change in the value of the pulse in relation to the constant and relatively small pause. It should also be noted that the quantitative change in the chemical composition of the weld metal during modulated effects is not critical for the joint strength, but this effect is still present. Carbon is found in steel usually in the form of the chemical compound Fe_3C, which is called cementite. With the increase in carbon content up to 1.2%: hardness, strength and elasticity of steel increase; plasticity and impact resistance decrease; weldability and machinability deteriorate.

More significant importance for the quality of mechanical characteristics have inclusions that are present be in the seam. Experimental comparative investigations of the content of non-metallic inclusions were carried out in order to detect solid impurities in metal of welded rollers, as well as gaseous inclusions. Samples No. 10, No. 11, No. 16 of alloy steel were investigated (St3.).

Comparative characteristic microgrins of the samples are shown in Fig. 6, Fig. 7, Fig. 8, Fig. 9.

x100 Sample 11

Figure 6. Non-metallic inclusions in the seam

x100 Sample 10

Figure 7. Non-metallic inclusions in the seam

x100 Sample 16

Figure 8. Non-metallic inclusions in the seam

x100 Sample 36

Figure 9. Non-metallic inclusions in the seam

A fairly accurate calculation based on metallographic investigations defined that all samples had small dark round inclusions – silicates and complex oxides, located randomly along the body.

Photos of comparative macrogrinds of the cross-section of the seam are presented in Fig. 10.

1 2 3 4

Figure 10. Macrogrinds of cross sections of sufraced rollers: 1, 2 – stationary mode; 3, 4 – mode with welding current modulation

It can be seen that the deposited rollers during processes with stationary arc and modulated current differ significantly. The presence of impurities is approximately the same (at first glance) in all samples. Detailed investigation shows that there are differences in the presence of inclusions during surfacing by stationary and modulated arc. The results of the investigations are presented in Table 4.

Table 4

Non-metallic inclusions in the metal of sufraced roller

Volume percentage of inclusions, %	
Stationary mode	0.75
Mode with modulation of parameters	0.65

Analysis of gas inclusions carried out for a large number of samples in averaged form is presented in Table. 5.

Table 5

Gas inclusions in the metal of sufraced roller

Share of gas inclusions, %	
Stationary mode	0.129
Mode with modulation of parameters	0.097

The results of the analysis of inclusions of various origins make it possible to conclude that while using modulated influences, they are notably lower, which is an additional factor in ensuring the strength characteristics (hardness, wear resistance) of the deposited roller and the seam made under flux.

The reduction of non-metallic and gaseous inclusions in the metal in the pulse mode of the modulated current can be explained by the influence of pulse (electrodynamic) action on the molten metal, which allows the bath to vibrate and thereby initiate the crushing of non-metallic inclusions. At the same time, the exit of gaseous inclusions to the surface bath is ensured.

All this is especially important while welding under flux, when the possibility of transition of non-metallic inclusions from the composition of the flux is particularly high.

While using modulation of the welding current, it is practically possible to achieve almost 30% reduction of inclusions.

It can be noticed that the surfaced rollers in the processes with stationary arc and modulated current differ significantly.

It is very important to form the structure of the weld metal under modulated actions. The size of the grain has a great influence on the steel properties. In advance, it can be noticed that during slow cooling during the hardening process, the metal acquires coarse-grained structure. Columnar-dendritic structure with large grains is also characteristic for welding under flux, where cooling of the weld metal occurs more slowly.

Analysis of materials in papers [14, 15, 16] shows that the fine-grained granular structure (grains, crystallites) increases the mechanical properties of the deposited metal or weld.

The change in grain size during welding with mode modulation is also explained by the change in the thermal cycle of the process.

From the above mentioned, it follows that one of the main tasks of electric arc welding in general and automatic welding under flux is the selection or organization of such a process that ensures certain finely dispersed structure of the weld metal, or at least insignificant increase in the grain size compared to the source material [17].

From the point of view of the structuring of the weld metal with the provision of minimum size of the crystallites (grains), the overheating area is the most problematic [18].

Determination of the grain size of the deposited metal was carried out according to GOST 5639-65 regarding to the microstructure. The results of measurements for different samples, respectively to different modulation modes are presented in Table. 6.

Table 6

Grain in the area of overheating

Grain size in the area of overheating		
Number in sequence	Sample No.	Grain size
1	Initial Sample	3–4
2	No. 1	5–6
3	No. 2	6–7
4	No. 3	5 – close to the seam root; 4 – close to the seam top
5	No. 4	5 – close to the seam root; 4–3 close to the seam top
6	No. 5	4–5 close to the seam root; 3 – close to the seam top
7	No. 6	5–6 close to the seam root; 3 – close to the seam top
8	No. 7	3–4
9	No. 8	3–4
10	No. 9	3–4
11	No. 10	4–5
12	No. 11	4
13	No.12	4–5
14	No. 13	5–6
15	No. 14	6
16	No. 15	5–6
17	No. 16	5–6
18	No. 17	5–6
19	No. 18	5–6
20	No. 19	4–6

Analysis of the measurement results shows that modulation of the welding current significantly affects the structure of the metal, ensuring either the preservation of the properties of the original material, or limiting grain growth. At the same time, it can be noted that there are modulation modes when there is no grain growth compared to the original sample. This effect can be explained by the electrodynamic effect of each current pulse in the modulation cycle, as well as by the increased movement of the liquid metal of the welding bath.

The changes in the structure of the deposited metal using modulated mode, indicated above, affect the qualitative and quantitative indicators of the operational characteristics of the product as a whole. First of all, this refers to the parameters of impact viscosity, hardness, etc. In this paper, a set of comparative investigations of the mechanical characteristics of surfacing metal was carried out.

Comparative values of impact toughness for welding under flux in the usual way and with process modulation are given in Table 7.

Table 7

Impact viscosity of the seam metal surfaced by different welding methods

Definition of impact viscosity		
Type of welding	Impact viscosity at various measurement temperatures	
	- 40^0C	- 60^0C
Stationary arc	8,0, 42,0, 70,0 Average 40	4,0, 66,0, 11,0 Average 27
Modulated process	66,0 91,0 70,0 Average 73.5	63,0, 74,0 98,0 Average 76

In the table 8 presents the results of microhardness determinations at several measurement points on TP-7-R device in different seam areas are given in Table 8.

Table 8

Results of measurements of the microhardness of samples sufracing metal

Microhardness				
Sample No.	Hardness HV	Hardness of the area of thermal influence, HV		Basic metal
		Coarse-grained area	Area of complete and incomplete crystallization	
Initial Sample	232, 221, 219, 221	221, 227, 219	221, 203, 180, 178	171, 175
1	199, 195, 210,199, 208	232, 210, 225	214, 210 199,197	
2	225, 227, 216, 227	238, 236	221, 197 195, 177	
3	227, 223, 221	214, 219	199, 183, 182	
4	221, 225, 225	227, 225	216, 221, 210,195	
5	214, 208, 229, 221	227, 214	201, 203, 192, 187	
6	223, 225, 219	229, 216	216, 214, 199,185	
7	223, 213, 229, 223,214	223, 204, 203	206, 197, 188,178	
8	225, 221, 225,	208, 214, 204	216, 204, 203, 195	
9	227, 223, 225	225, 208, 221	208, 195, 188, 187	
10	212, 212, 221	216, 214,212	214, 203, 192, 187	
11	208, 223, 221	206, 206, 221	206, 193, 195, 187	
12	221, 223, 214, 210	214, 203, 192	206, 195, 182, 187	
13	241, 232, 239, 231	251, 257, 269	201, 193, 193, 182	
14	221, 232, 232,	229, 208, 208	197, 180, 172	
15	234, 232, 244, 241	225, 227, 225	212, 195, 187	
16	244, 234, 229, 223	219, 225, 216	216, 218, 189, 178	
17	232, 239, 232	212, 219, 219	203, 201, 177, 177	
18	246, 239, 239, 241	249, 244, 268	239, 239, 236, 193	
19	232, 223, 223	221, 236, 236	214, 214, 188, 187	

The results of comparative investigations of the welds mechanical properties, obtained at several points, are given in Table 9.

Table 9

Results of mechanical properties investigations

Mechanical properties of samples				
Welding method	Mechanical properties			
Stationary arc	Fluidity limit, kgf/mm	Temporary resistance to rupture, MPa	Relative elongation, %	Relative narrowing, %
	310, 306, 306 Average 308	473, 470, 470 Average 471	27,6; 30,3; 30,6; Average 28,3	55,6; 55,6; 53,3 Average 54,5
Modulated mode	283, 307, 318 Average 303	452, 450, 473 Average 471	28,0; 29,3; 29,3 Average 28,8	59,9; 59,9; 59,9 Average 59,9

The appearance of some welded samples after testing is presented in Fig. 11.

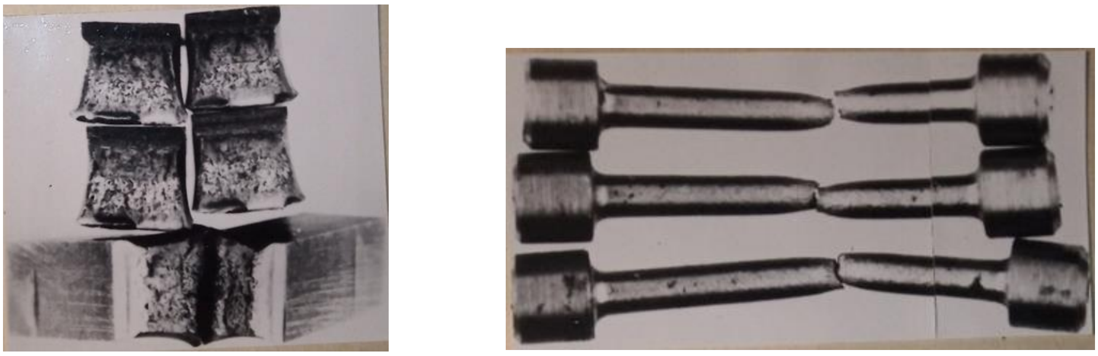


Figure 11. Different types of mechanical tests of samples welded under flux by different types of welding

The mechanical properties of the welded joint by different modes under the flux (impact strength at different measurement points with subsequent averaging) are shown in Table 10.

Table 10

Viscosity in cross section of different areas of surfacing of seam metal performed by different welding methods

Impact viscosity of the seam metal J/cm^2									
Welding method	Seam center at temperature, ^{0}C	Seam area at temperatures, ^{0}C				Fusion line at temperature, ^{0}C			
	+20	-40	-60	+20	-40	-60	+20	-40	-60
Stationary arc	100	5.0	4.0	126	5.0	5.0	104	45	30
	87	37	4.0	85	5.0	10.0	114	5.0	9.0
	37	40	9.0	144	15.0	27.0	100	3.7	4.0
Average	108	27	6	118	8	14	106	25	5.3
Modulated process	133	55	45	136	67	32	115	26	7.0
	126	62	15	120	135	5.0	144	12	47.0
	117	110	7.0	132	59	15.0	112	73	27.0
Average	126	75	22	124	94	18	123	57.8	27

From the numerous results presented in Table. 7, Table 8 and Table. 9, Table 10, it can be concluded that welding under flux with the application of the welding current modulation makes it possible not only not to deteriorate the mechanical characteristics of the welds, but in some cases even to modulation increase modulation these indicators.

The analysis of the seam structures made it possible to determine that the seam structure of the original sample is bainite with pre-eutectoid ferrite. The overheating zone consists of ferrite, pearlite and bainite. The structure of seams of samples No. 1 – No. 16 is cast bainite. Pre-eutectoid ferrite stands out on the boundaries of primary crystallites. The heat-affected zone in all samples consists of an overheating zone (area of large grains), a zone of complete (area of fine grains) and incomplete recrystallization. The structure of the heat-affected zone is bainite and ferrite. In sample No. 1, in the seam and the heat-affected zone, in addition to the bainite and ferrite components, there are also areas of pearlite. The bainite component in sample No. 1 is smaller than in the others. The structure of the seams of the studied samples No. 7 – No. 12 is bainite with layers of pre-eutectoid ferrite. In samples No. 13 – No. 19, the ferrite layers are thin. The structure of the near-seam zone and the overheating zone in samples No. 7 – No. 12, adjacent to the fusion line, is a mixture of the ferrite component. It is followed by zones of incomplete and complete recrystallization. In samples from No. 13 to No. 19, the amount of the bainite component in the seam and the overheating zone increases. Obviously, for this reason, the hardness in the samples is increased, and other mechanical characteristics are also improved.

It can be noted that the viscous properties significantly deteriorate against the background of the increase in the linear energy of welding, that is, heat deposits, which are inherent in high-performance welding under flux. In the case of modulated modes application, the viscosity indicators increase in all areas of the seam, which is especially noticeable at low temperatures.

Selective welding processes of other welding modes were carried out. It was determined that the trends of influence of modulated modes on the characteristics of the welded joint are preserved.

From the conducted cycle of experimental investigations, the following advantages can be determined for the process of welding under flux with mode modulation [19] in comparison with the stationary mode:

1. Improvement of the quality characteristics of welded joints and the layer applied during surfacing (improvement of seam formation regardless of spatial position, increase of homogeneity of the chemical composition throughout the volume, grinding of the structure of the weld seam in the area of thermal influence).

2. The possibility of obtaining the given geometry of the weld by changing the modulation parameters.

3. Obtaining the necessary chemical composition of the deposited metal to ensure the specified mechanical properties. Improvement of the mechanical properties of the resulting welded structures, associated with a significant reduction of the thermally affected zone and grinding of its structure. These advantages are due to the strengthening of the influence of hydrodynamic processes in the molten metal, which contribute to intensive degassing of the welding bath and the formation of a more uniform structure of the melt volume.

4. The reduction of heat deposits in the product leads to the reduction of the zone of thermal influence, which ensures the preservation of the chemical and mechanical properties of the metal.

Conclusions. Automatic flux-cored welding with controlled periodic change of modes has a number of features that contribute to the formation of the structure of the metal carcass, its chemical composition, physical and mechanical characteristics, and operational properties. Carried out experimental investigations showed that the parameters of the welding current (frequency, sparring) determine the degree of influence on the physical and mechanical characteristics of the metal welded joint and in most cases improve them compared to these characteristics in the stationary mode. The improvement of the operational properties of the welded joint for the modes of operation in automatic electric arc welding under flux is associated with the change (grinding) of the structure of the weld metal, decrease in the level of solid and gaseous inclusions in the deposited metal. The field of application of automatic electric arc welding under flux in order to obtain metal welds with improved operational characteristics can be expanded due to the use of controlled modulated modes. The creation of improved systems for the formation of welding current modulation modes is possible on the basis of modern technical solutions using the achievements of mechatronics.

References

1. Avtomaticheskaja dugovaja svarka. Svarka s primeneniem svarochnykh traktorov, flyusov. [E'lektronnyj resurs]. URL:http://www.tdsplav74.ru/avtomaticheskaja-dugovaja-svarka (dataobrashcheniya: 13.03.2012).
2. Valeev D. A., Knjazʹkov A. F. Primenenie moduljacii toka pri avtomatycheskoj svarke pod fljusom. Svarochnoe proizvodstvo. Tomsk. No. 2. P. 32–33.
3. Merkulov B. A. i dr. Tekhnolohycheskie osobennosti svarki pul'siruyushchej dugoj pod flyusom. Svarochnoe proizvodstvo. 1975. No. 3. P. 13–15.
4. Pokhodnya I. K., Holovko V. V., Sheyko P. P. Vliyanie rezhymov svarki pod flyusom pul'siruyushchej dugoj na glubinu proplavleniya osnovnogo metalla. Avtomaticheskaja svarka. 1996. No. 5. P. 3–7.
5. Gorkunov E'. S., Saraev Ju. N., Zadvorkin S. M., Putilova E. A. Vlijanie technologycheskich rezchymov svarki na fiziko-mechanicheskie charakteristiki metalla razlichnych zon svarnych soedinenij nyzkolegirovannoj stali. Voprosy materyalovedenija. 2015. No. 1. P. 120–126.
6. Rjabcev Y. A., Kuskov Ju. M., Kondratʹev Y. A., Černjak Ja. P., Rjabcev Y. Y. Materialy ie'ne'rgosberegajushchie technologii naplavki dlja vosstanovlenija iizgotovlenija detalej mashin imechanizmov. Avtomaticheskaja svarka. 2007. No. 03. P. 21–27.
7. Lypodaev V. N., Snisar' V. V. Vliyanie modulyatsii svarochnogo toka na strukturu i treshchinostojkost' shvov. Avtomaticheskaya svarka. 1991. No. 2. P. 26–30.
8. Nazarchuk A. T., Snysarʹ V. V., Demchenko Ye. L. Porcyonnoe teplovlozchenie kak sposob upravlenija strukturoj metalla shva i ZTV/ Avtomaticheskaja svarka. 2003. No. 12. P. 39–42.
9. Grabin V. F., Golovko V. V., Novikova D. P. Osobennosti struktury metalla shvov pri svarke pod fljusom pulʹsirujushchej dugoj. Avtomatycheskaja svarka. 1995. No. 8. P. 3–10.
10. Boldyrev A. M. O mechanizme formirovanija struktury metalla shva pri vvedenii nyzkochastotnych kolebanij v svarochnuju vannu. Svarochnoe proizvodstvo. 1976. No. 2. P. 1–3.
11. Lebedev V. A., Tyshchenko V. A. O vybore oborudovaniya dlya naplavki pul'siruyushchej dugoj matrits shtampov. Avtomaticheskaya svarka. 1997. No. 8. P. 51–52.
12. Lebedev V. A., Zhuk G. V. Sistema upravleniya dozirovannoy podachej e’lektrodnoj provoloki pri mekhanizirovannoj e'lektrodugovoj svarke. E’le’ktrotekhnichni ta komp’yuterni systemy. 2018. No. 28. P. 79–87.
13. Sidnyaev N. I. Teoriya planirovaniya e'ksperimenta i analiz statisticheskikh dannykh: uchebnik i praktikum dlya bakalavrata i magistratury. Moskva: Izdatel'stvo Yurayt, 2018. 495 p.
14. Gryhorash V. V. Upravleniye kristallizaciej metalla shva s celʹju povyshenija technologicheskoj prochnosti svarnych soedinenij: dissertacija kand. techn. nauk: K.: KPY, 1991. 238 p.
15. Singh P. K., Patel D., Prasad S. B. (2016) Development of vibratory welding technique and tensile properties investigation of shielded metal arc welded joints. Indian Journal of Science and Technology. No. 9 (35). P. 1–6. DOI: https://doi.org/10.17485/ijst/2016/v9i35/92846
16. Murtazina Z. Kh., Konovalov A. V. Vliyanie svarochnogo termicheskogo tsikla na rost zerna austenite. “Neftegaz”. No. 10 oktyabr' 2018. P. 50–53.
17. Kozlov E'.V., Zhdanov A. N., Koneva N. A. Izmel'chenie razmera zerna kak osnovnoj resurs povysheniya predela tekuchesti. Vestnik THU. T. 8. Vyp. 4. 2003. P. 509–513.
18. Kuzʹmenko V. H., Galinich V. Y., Tokarev V. S. O charakternych zonach svarochnoj vanny pri dugovoj svarke pod fljusom. Avtomaticheskaja svarka. 1997. No. 5. P. 24–27.
19. Merkulov B. A. Sposoby modulirovanija svarochnogo toka periodicheskoj podachej e'lektrodnoj provoloki. Svarochnoe proizvodstvo. 1985. No. 3. P. 4–6.

Список використаних джерел

1. Автоматическая дуговая сварка. Сварка с применением сварочных тракторов, флюсов. URL: http://www.tdsplav74.ru/avtomaticheskaja-dugovaja-svarka. (дата обращения: 13.03.2012).

2. Валеев Д. А., Князьков А. Ф. Применение модуляции тока при автоматической сварке под флюсом. Сварочное производство. № 2. С. 32–33.
3. Меркулов Б. А. и др. Технологические особенности сварки пульсирующей дугой под флюсом. Сварочное производство. 1975. № 3. С. 13–15.
4. Походня И. К., Головко В. В., Шейко П. П. Влияние режимов сварки под флюсом пульсирующей дугой на глубину проплавления основного металла. Автоматическая сварка. 1996. № 5. С. 3–7.
5. Горкунов Э. С., Сараев Ю. Н., Задворкин С. М., Путилова Е. А. Влияние технологических режимов сварки на физико-механические характеристики металла различных зон сварных соединений низколегированной стали. Вопросы материаловедения. 2015. № 1. С. 120–126.
6. Рябцев И. А., Кусков Ю. М., Кондратьев И. А., Черняк Я. П., Рябцев И. И. Материалы и энергосберегающие технологии наплавки для восстановления и изготовления деталей машин и механизмов. Автоматическая сварка. 2007. № 03. С. 21–27.
7. Липодаев В. Н., Снисарь В.В. Влияние модуляции сварочного тока на структуру и трещиностойкость швов. Автоматическая сварка. 1991. № 2. С. 26–30.
8. Назарчук А. Т., Снисарь В. В., Демченко Э. Л. Порционное тепловложение как способ управления структурой металла шва и ЗТВ. Автоматическая сварка. 2003. № 12. С. 39–42.
9. Грабин В. Ф., Головко В. В., Новикова Д. П. Особенности структуры металла швов при сварке под флюсом пульсирующей дугой. Автоматическая сварка. 1995. № 8. С. 3–10.
10. Болдырев А. М. О механизме формирования структуры металла шва при введении низкочастотных колебаний в сварочную ванну. Сварочное производство. 1976. № 2. С. 1–3.
11. Лебедев В. А., Тищенко В. А. О выборе оборудования для наплавки пульсирующей дугой матриц штампов. Автоматическая сварка. 1997. № 8. С. 51–52.
12. Лебедев В. А., Жук Г. В. Система управления дозированной подачей электродной проволоки при механизированной электродуговой сварке. Електротехнічні та комп'ютерні системи. 2018. № 28. С. 79–87.
13. Сидняев Н. И. Теория планирования эксперимента и анализ статистических данных: учебник и практикум для бакалаврата и магистратуры. Москва: Издательство Юрайт, 2018. 495 с.
14. Григораш В. В. Управление кристаллизацией металла шва с целью повышения технологической прочности сварных соединений: дыс. … канд. техн. наук: К.: КПИ, 1991. 238 с.
20. Singh P. K., Patel D., Prasad S. B. (2016) Development of vibratory welding technique and tensile properties investigation of shielded metal arc welded joints. Indian Journal of Science and Technology. No. 9 (35). P. 1–6.
15. Муртазина З. Х., Коновалов А. В. Влияние сварочного термического цикла на рост зерна аустенита Территория «Нефтегаз». № 10. Октябрь. 2018. С. 50–53. DOI: https://doi.org/10.17485/ijst/2016/v9i35/92846
16. Козлов Э. В., Жданов А. Н., Конева Н. А. Измельчение размера зерна как основной ресурс повышения предела текучести. Вестник ТГУ. Т. 8. Вып. 4. 2003. С. 509–513.
17. Кузьменко В. Г., Галинич В. И., Токарев В. С. О характерных зонах сварочной ванны при дуговой сварке под флюсом. Автоматическая сварка. 1997. № 5. С. 24–27.
18. Меркулов Б. А. Способы модулирования сварочного тока периодической подачей электродной проволоки. Сварочное производство. 1985. № 3. С. 4–6.

УДК621.791.03

ДЕЯКІ ОСОБЛИВОСТІ АВТОМАТИЧНОГО ЕЛЕКТРОДУГОВОГО НАПЛАВЛЕННЯ ПІД ФЛЮСОМ З КЕРОВАНОЮ ПЕРІОДИЧНОЮ ЗМІНОЮ РЕЖИМІВ

Володимир Лебедєв[1]; ВікторТищенко[1]; Сергій Лой[2]; Олексій Халімовський[1]

[1]ІЕЗ імені Є. О. Патона НАН України, Київ, Україна
[1]Національний університет кораблебудування імені адмірала Макарова, Миколаїв, Україна

Резюме. *Процес автоматичного електродугового наплавлення під флюсом має ряд особливостей. За рахунок використання в цих процесах керованих модульованих режимів можливо покращити* *експлуатаційні характеристики зварних швів металу. Типове обладнання дає можливість реалізувати низькочастотні модульовані імпульсні режими з максимальними частотами порядку кількох герц. Такі межі частот зумовлені динамічними властивостями зварювального обладнання, виконаного на базі механізму подачі зварювального дроту з електроприводом постійного струму. Проведений цикл експериментальних досліджень дозволив визначити переваги процесу зварювання з модуляцією режимів у порівнянні зі зварюванням за стаціонарного режиму. Встановлено, що параметри струму зварювання (частота, шпаруватість) визначають ступінь впливу на фізико-механічні характеристики металу зварного з'єднання і в більшості випадків покращують їх у порівнянні з цими характеристиками за стаціонарного режиму. За рахунок зміни параметрів модуляції виникає можливість отримання заданої геометрії шва та підвищення однорідності хімічного складу по всьому об'єму зони розплавленого металу. Відзначені особливості утворюються за рахунок посилення гідродинамічних процесів у цій зоні. Наслідки такої дії призводять до подрібнення структури металу у зварному шві зони термічного впливу та створення умов, які сприяють інтенсивній дегазації зварювальної ванни й рівномірнішому об'єму розплаву. Результати аналізу дозволяють зробити висновок, що використання модульованих впливів знижує наявність включень різного походження. Застосуванням модуляції зварювального струму можна досягти зниження включень зі складу флюсу практично на 30%. Таке їх зменшення є додатковим фактором забезпечення характеристик міцності (твердості, зносостійкості) наплавленого валика й зварного шва. Таким чином, розроблення та застосування автоматичного електродугового наплавлення під флюсом з керованою періодичною зміною режимів дозволяє значно розширити можливості традиційних технологічних процесів наплавлення, що безпосередньо призведе до підвищення ефективності зварювального виробництва.*

Ключові слова: *електрична дуга, автоматичне наплавлення, імпульсний режим, електрод що плавиться, флюс, шпаруватість.*

https://doi.org/10.33108/visnyk_tntu2022.02.101 *Отримано 11.03.2022*