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Influence of Weld Pool Low-Frequency Oscillations on the Formation of Crystallites' Size and Welded Metal Microstructure

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On the analysis of last researches dedicated an increase of welding constructions technological strength with periodical effect on weld pool melt its established insufficiency knowledge about influence on formation of weld metal by oscillations with frequency range up to 5 Hz. Based on this, the result of researches is presented of the influence of harmonic mechanical trans-verse weld pool oscillations with a frequency of 2.5–4.5 Hz and an amplitude of 0.003–0.007 m ranges to formation of crystallite size and the microstructural components of weld metal obtained by GMAW with feeding of a low alloyed melting wire onto a base of construction medium carbon steel. The crystallite size analysis is got on the contour graphs base of crystallite size dependence from oscillations parameters and parameters of technological mode: ν—frequency; A—amplitude; V—surfacing speed and I—amperage of arc current. This dependence is model obtained by least squares method of regression analysis by the plan of experiments by 'Latin squares' method. Amplitude–frequency characteristics influence to a formation of structural components of weld metal microstructure is researched by the optical microscopy methods. Amplitude–frequency characteristics influence to a formation of structural components of weld metal microstructure which are contributed to increase of weld metal hardness value is researched, the influence of crystal-

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lite size value on weld metal hardness, as well. The importance of this work is in formation trends to get of maximum effective welded metal microstructure with minimum material and energy resources and simplicity construction of an installation for surfacing mechanized as well.

Key words: arc surfacing, weld pool oscillations, crystallites size.

З аналізу останніх досліджень, присвячених підвищенню технологічної міцності зварювальних конструкцій за періодичного впливу на розтоп зварювальної ванни, встановлено, що недостатньо знань щодо впливу на формування металу шва в умовах коливань з частотним діапазоном до 5 Гц. Відповідно наведено аналіз впливу гармонічних механічних поперечних коливань зварювальної ванни з частотою 2,5–4,5 Гц та амплітудою 0,003–0,007 м на формування розміру кристалітів та структурних складових металу шва у випадку автоматизованого натоплення у CO_2 низьколеґованим дротом на зразки з конструкційної середньовуглецевої сталі. Аналіз розміру кристалітів проведено на основі контурних графіків, побудованих на базі залежності розміру кристалітів від параметрів коливань та параметра технологічного режиму: ν — частоти; A — амплітуди; V — швидкості натоплення та I — сили струму зварювальної дуги. Ця залежність є моделлю, яка отримана методом найменших квадратів регресійного аналізу за планом експериментів, що створено на базі методу «латинських квадратів». Дослідження впливу амплітудно-частотних характеристик коливань на формування структурних компонентів мікроструктури металу шва здійснювали методами оптичної мікроскопії. Досліджено вплив амплітудно-частотних характеристик на формування структурних компонентів мікроструктури металу шва, які сприяли підвищенню твердості металу шва, а також вплив величини розміру кристалітів на твердість металу шва. Важливість даної роботи полягає у формуванні тенденцій одержання максимально ефективної мікроструктури зварного металу з мінімальними матеріально-енергетичними витратами на базі простої за конструкцією установки для натоплення.

Ключові слова: дугове натоплення, коливання зварювальної ванни, розмір кристаліту.

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1. INTRODUCTION

Increasing of welding constructions technological strength is one of the actual challenges today. It is known that a significant strength increase, hardness in particular, is a result of increasing the degree of weld metal dispersion crystallites. One of the simplest and cheapest ways of weld metal microstructure formation is mechanical harmonic weld pool or welding tool oscillations application. Nowadays, the more researched and informed field of knowledge is influence of oscillations over 5 Hz [1–3], by the other hand, the characteristic changes in the microstructure is already has observed at a frequency value of 2.5 Hz with an amplitude value at some microns [4], that determines the need of additionally researches in field of oscillation with frequency range from 2.5 to 5 Hz.

2. EXPERIMENTAL

Installation for surfacing provided weld pool oscillations had been created for research influence of low-frequency oscillations on microstructure of welded metal. The surfacing is performed with a feed melting wire ∅1.2 mm directly into the arc zone due to a semi-automatic wire feeder *1* (Table 1, Fig. 1).

Arc current is regulated by setting the appropriate feed rate of electrode wire with the appropriate switches on the control panel of the wire feeder device. An arc current magnitude is controlled by an ammeter is set on the front panel of power supply *2* is rectifier welding universal VDU-506. The rectilinear movement of the welding torch *3* carried out due to movable frame *4* where welding torch is fixed. Movement speed is smoothly set by the corresponding toggle switch on the control panel of a movable frame. Oscillation process of sample for

TABLE 1. Nomenclature of basic units of the surfacing installation and welding materials.

Equipment and materials	The model	The manufacturer	Country of production
Semi-automatic wire feeder	PSh 107V	The Pilot Paton Plant	USSR
Rectifier welding universal	VDU-506	The plant 'СиМЗ'	Ukraine
Welding torch	Prototype	The Pilot Paton Plant	Ukraine
Movable frame	Prototype	The Pilot Paton Plant	Ukraine
Stepper motor	Kinco-K306-24AT	Kinco Automation	PRC
Movable plate	Prototype	Ilnitsky factory of mechanical welding equipment	Ukraine
Control block	Prototype	Ilnitsky factory of mechanical welding equipment	Ukraine
Programming console	Kinco MD 224L-11	Kinco Automation	PRC
Material of samples	Ст 3 (A568M)	–	Ukraine
Solid welding wire	ER70S-6	–	PRC

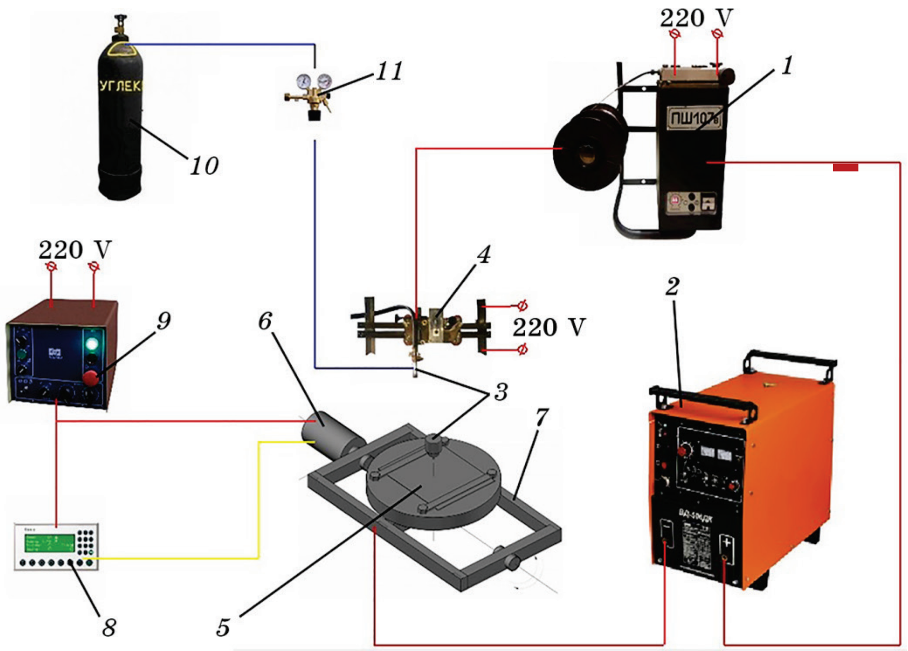


Fig. 1. Structural scheme of the surfacing installation: *1*—semi-automatic wire feeder; *2*—power supply; *3*—welding torch; *4*—welding torch movable frame; *5*—sample for surfacing; *6*—stepper motor; *7*—movable plate; *8*—control console; *9*—control block; *10*—CO_2 gas balloon; *11*—gas reducer. *Red line*—power main; *blue line*—gas main; *yellow line*—main for data input.

surfacing *5* took place due to movable plate, which is able to move in an arc of a circle with centre O to a certain angle α (Fig. 2) is determines of the magnitude of oscillation amplitude *A*.

The circle centre is axis parallel to the surfacing axis and through which passed the shaft of the stepper motor *6*, which brought into oscillation the movable plate *7*. Stepper motor parameters are entered thanks to the control console *8*. Starting of the stepper motor, its stop, control, programming and processing of an oscillation mode is carried out by the control block *9* on the basis of the controller of the PLC Kinco-K306-24AT. CO_2 supply to the arc zone is carried out from a gas balloon *10*, and gas flow is regulated by a reducer *11*. CO_2 consumption is constant in all experiments and is range to 9–12 l/min.

All samples for surfacing are metal plates with a thickness of 8 mm from sheet steel. The samples sizes are not constants, and they had at the range by the width of 30–25 mm and by the length—120–180 mm.

Before surfacing, all surfaces of each sample are cleaned from a protected coating, pollution and rust by grinding machine. The surface degreasing is made by acetone.

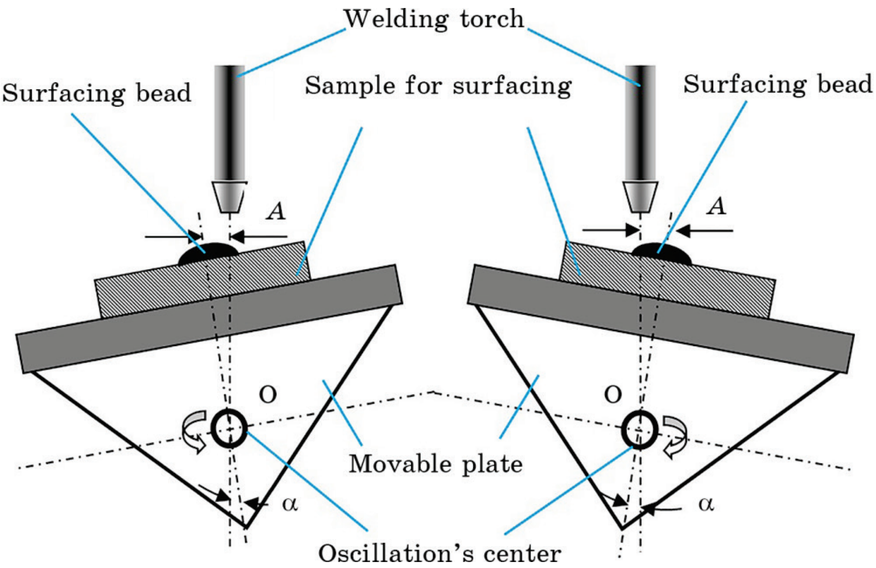


Fig. 2. Scheme of movable plate traverse oscillations, where A—oscillations amplitude, α—the deviation angle from the surfacing process axis, O—oscillation's centre.

An influence of oscillation mode with frequency $\nu = 2.5–4.5$ Hz and amplitude $A = 0.003–0.007$ m ranges on crystallite size δ and corresponding average hardness values B of welded metal is researched. Appropriate samples are obtained on to technological modes with current $I = 100–200$ A and velocity $V = 0.0028–0.0072$ m/s ranges. Experiments are carried out according to the plan of 'Latin squares' [5] for 25 samples obtained by MAG surfacing in CO_2. For comparison, 5 samples are obtained without weld pool oscillations by the same surfacing type, it's are been designated*.

For further researches, a micro section is obtained by cutting some part of the sample, followed by mechanical and chemical treatment, which includes grinding, polishing and chemical etching. Cleanliness class of research surface of micro section is 14. Weld metal crystallite size value are measured in upper, medium and root part of bead and average hardness value B (Table 2).

In this work, a separate crystal of a polycrystalline conglomerate, which is bounded by adjacent surfaces–grain boundaries, is considered a crystallite. The grain size is measured as the average value of random cross sections of grains in the plane of the metallographic section.

All metallographic researches are carried out on a NEOPHOT-32 microscope and microstructures views ware obtained by an Olympus digital camera. The hardness value is measured by Vickers using a hardness tester LECO M-400.

TABLE 2. The crystallites size value δ in the weld metal of surfacing beads obtained at the appropriate oscillatory and technological modes.

Experiment number	*I*, A	*V*, m/s	ν, Hz	*A*, m	δ, μm			$B\cdot10^7$, Pa
					Upper part	Medium part	Root part	
1*	100	0.0028	–	–	258	208	82	170
1	100	0.0028	4	0.007	65	113	57	192
2	100	0.0039	3.5	0.006	105	108	54	202
3	100	0.005	4.5	0.003	90	101	46	222
4	100	0.0061	2.5	0.004	25	67	26	226
5	100	0.0072	3	0.005	48	58	37	211
6	125	0.0028	3.5	0.003	78	90	57	207
7*	125	0.0039	–	–	127	148	46	167
7	125	0.0039	3	0.007	67	116	56	220
8	125	0.005	4	0.004	69	100	35	226
9	125	0.0061	4.5	0.005	114	70	59	237
10	125	0.0072	2.5	0.006	–	55	26	270
11	150	0.0028	4.5	0.006	117	120	42	217
12	150	0.0039	4	0.005	97	132	45	229
13*	150	0.005	–	–	36	113	65	214
13	150	0.005	2.5	0.007	36	43	39	211
14	150	0.0061	3	0.003	79	159	48	224
15	150	0.0072	3.5	0.004	110	79	30	253
16	175	0.0028	3	0.004	185	176	64	206
17	175	0.0039	2.5	0.003	48.5	52.5	30	184
18	175	0.005	3.5	0.005	130	133.5	48,5	215
19*	175	0.0061	–	–	88.6	133	34	222
19	175	0.0061	4	0.006	155	130	43	226
20	175	0.0072	4.5	0.007	55	77	57	213
21	200	0.0028	2.5	0.005	–	174	53.3	193
22	200	0.0039	4.5	0.004	60	90	48.3	224
23	200	0.005	3	0.006	147	195	47	220
24	200	0.0061	3.5	0.007	162	108.3	30	213
25*	200	0.0072	–	–	50	53	24	200
25	200	0.0072	4	0.003	109	89	40	196

3. RESULTS AND DISCUSSION

With data obtained (Table 2) shows a tendency to dispersion degree increase due to oscillations in comparison without those is observed in not whole amplitude–frequency range, in addition, a hardness values *B* in some surfacing samples are higher where the crystallite size is larger (Fig. 3). Thus, an increase the microstructure dispersion degree is not the only way to corresponding increase the hardness can be assumed. One of the probable reasons is prevail of microstructure com-

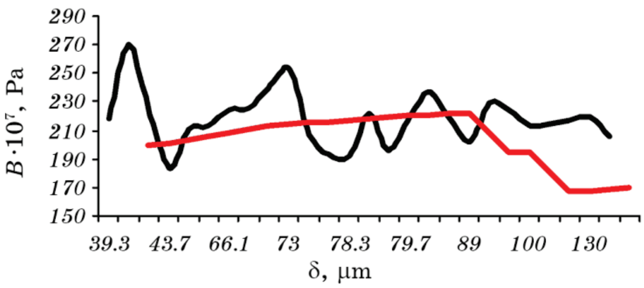


Fig. 3. The graph of mean value of hardness dependence of welded metal B on the crystallite size δ, according with the data in Table 2. *Black line*—with oscillations applied; *red line*—without oscillations (interpolated according by data marked*).

ponents formation, in particular acicular ferrite [6], that contributes hardness value increase over increase of dispersion degree of microstructure. This is assumption stipulates further research of weld pool oscillations influence on microstructure not only as an influence factor on crystallite size but the one of influence on certain structure components formation.

The main influencing factors to degree of microstructure dispersion under mechanical oscillations are fluctuations in the temperature gradient and diffusion processes in the zone of the crystallization front, fragmentation of grains and an obstruction to its growth as well. There is not currently theory of describe the formation of a microstructure taking into causes these factors, which determines the use of statistical methods for processing experimental data as the most convenient and accurate for technological needs.

Processing of measurement results, δ is carried out by the least squares method of regression analysis [7] using the STATISTICA software and represents is the model of dependence of the response δ on independent factors: I, V, A, ν:

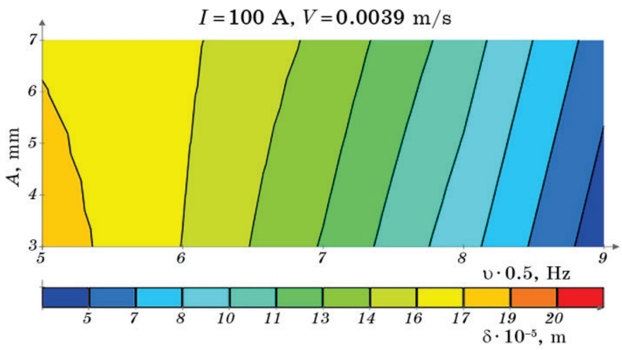
$$\begin{aligned}\delta = {} & 0.000861939780195999 - 0.0000045746805437794 4I - \\ & - 0.000152825723295094\nu - 0.099658715277177IVA + \\ & + 0.000125847261742664IV\nu + 0.0663135721635428IV^2 + \\ & + 0.000103968124488349IA\nu^2 - 0.0378703542888321IVA\nu^2 + \\ & + 13.5922416750269IA\nu V^2 + 0.00000000417935502751238I^2\nu - \\ & - 0.000000548232819770337V\nu I^2 + 0.00174124657326777V\nu^2 + \\ & + 2.00770982113061AV\nu^2 + 3.40689322091218\nu V^2 - \\ & - 0.00593263564907643A\nu^2 - 3331.1722125233V^3.\end{aligned} \quad (1)$$

Model adequacy is evaluated by Fisher's, χ^2 criteria and a determine of minimization criteria accordance of residual vector ε. The significance of each of factors of obtained model is checked using t-statistics. Model (1) is adequate and has a degree of compliance with true dependence at the level of 86–89%.

According to the obtained regression model (1), contour graphs of a depend crystalites size value from amplitude and frequency values are obtained for each of arc current and surfacing velosity rate values, from the analysis of which it is found that the minimum of crystallite size are most ofren formed at frequency values 2.5 and 4.5 Hz. Amplitude value A is determined by relation of arc current I and surfacing speed V (Fig. 4, *a* and *b*). Also, the relation allows to choose an technologicals modes where the least crystallite size formation posible both at frequency values 2.5 Hz and at 4.5 Hz (Fig. 4, *c* and *d*). In general, there is no general relationship between technological and oscillatory parameters for crystalites formation of the minimum size.

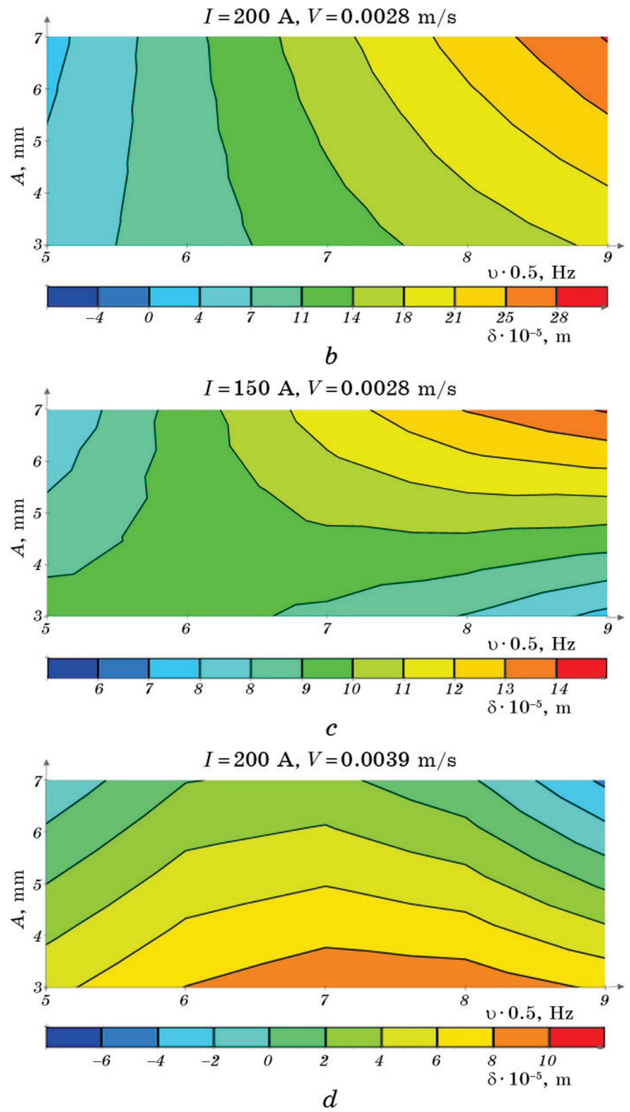
From crystallite size values analysis (Table 2) and repression model (1) follows that the size can be reduced by at least 1.57–2.7 times compared to samples obtained without oscillations, but when the surfacing with arc current of 200 A crystallite size can on the contrary, increase due to oscillations.

The main difference between the samples obtained by oscillations and those obtained without ones is not only to increase the degree of microstructure dispersion, but also to increase the useful structural components.



a

Fig. 4. Contour graphs of crystallites size dependence from the amplitude–frequency parameters of welding bath oscillations obtained at different technological modes: the least crystallite size formation at $\nu = 4.5$ Hz, $A = 3$–5 mm (*a*); the least crystallite size formation at $\nu = 2.5$ Hz, $A = 6$–7 mm (*b*); the least crystallite size formation both at $\nu = 2.5$ Hz, $A = 6$–7 mm and at $\nu = 4.5$ Hz, $A = 3$ mm (*c*); the least crystallite size formation both at $\nu = 2.5$ Hz, $A = 6$–7 mm and at $\nu =$ $= 4.5$ Hz, $A = 6$–7 mm (*d*).



Continuation of Fig. 4.

Well, the samples obtained without the weld pool oscillations influence have a classical ferrite-pearlite structure with rather wide cast crystallites, as well as with ferrite layers along the boundaries of cast crystallites, which represent the release of polygonal ferrite (Fig. 5, *a*–*c*). The influence of oscillations significantly improves the microstructure, various forms of ferrite are observed (Fig. 5, *d*): polygonal—in the form of thin layers along the boundaries of cast crystallites; polyhedral—in the form of individual or groups of grains, which are mostly adjacent to the polygonal ferrite; lamellar ferrite with an ordered 2nd phase, which is the release of carbides in the form of parallel series in the ferrite matrix. In addition, acicular ferrite is observed in the centre of the cast crystallites, as well as small areas of perlite that have the appearance of small dark secretions adjacent to the ferrite grains. Acicular ferrite is accompanied by the release of MAC-phase, which also increases the hardness and toughness. Also, oscillations contribute to a significant reduction or even get rid of such harmful structural components as the Widmanstätt structure.

In terms of the influence on the microstructure, the oscillatory modes differ significantly from each other in the qualitative change of the microstructural components, but very significantly in their quantitative relation. The general tendency is that oscillations promote not

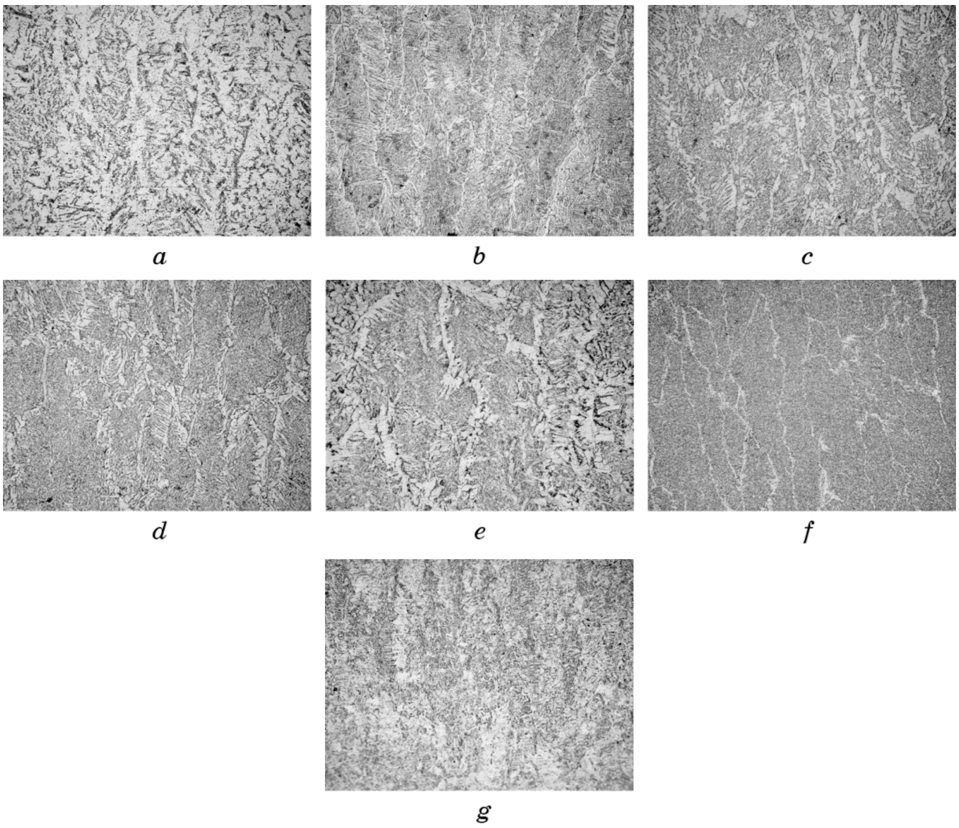


Fig. 5. Views of typical microstructure of welded metal beads obtained without oscillations and with weld pool oscillations (×200) (*a*–*c*): characteristic microstructure (*d*); microstructure with acicular ferrite in a basket-weave form (*e*); microstructure with fine-acicular ferrite (*f*); microstructure of mixture of upper and lower bainite (*g*).

only to an increase in the fraction of acicular ferrite, as the most useful component, but also to its various forms (Fig. 5, *e* and *f*).

The best microstructure of the welded metal is obtained in the mode $I = 125$ A; $V = 0.0072$ m/s; $A = 0.006$ m; $\nu = 2.5$ Hz and is a mixture of upper and lower bainite (Fig. 5, *g*).

4. CONCLUSION

The analysis of weld pool oscillations influences to the crystallites size of weld metal on the base of regression model obtained is done. From this one is established that the least crystallite size value is most often formed at frequencies with ranges 2.5 and 4.5 Hz in dependence on the ratio of current and speed surfacing which determine the effective amplitude value. That is confirmed result of work [4], but that crystallite size can be reduced by at least 1.57–2.7 times compared to samples obtained without oscillations, that is much lower in comparison with results of work [4] where crystallites size is reduced in 10 times. This is due with different conditions caring out experiments that are proved of results work [1] where crystallites size is reduced in 2.7 times at frequency value 75 Hz. In general, the tendency of oscillation application is that mechanical properties increase the more the large values of amplitude and frequency especially.

From the analysis of weld metal microstructure, it is following that the oscillations significantly improve the microstructure and increase the useful structural components number such as acicular and plate ferrite, which can be formed not only in the base microstructure but also in the crystallites body. As well as, the oscillations get rid structural components nearly or at all from harmful structural, such as the Widmanstätt structure.

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