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INFLUENCE OF THE FREQUENCY OF EXTERNAL ELECTROMAGNETIC FIELD ON THE STRUCTURE OF 09G2S STEEL WELDED JOINTS

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ABSTRACT

Features of metal structure in 09G2S steel welded joints were studied in welding with application of a longitudinal external electromagnetic field. The influence of field frequency ($f = 2$; 12; 50 Hz) on phase composition, microstructure and microhardness of welded joint metal was studied. It was found that significant changes of structural parameters in the weld metal and in the subzones of the heat-affected zone (HAZ) take place in the studied frequency range. The influence of frequency of electromagnetic effect in low-alloyed steel welding is more pronounced in the metal of the weld and HAZ in the overheated subzone (coarse grain). Application of $f = 12$ Hz ensured a uniform microhardness level both in the weld metal and in the HAZ subzones, as well as grain structure refinement in the overheated subzone (I HAZ) of 09G2S steel welded joint.

KEYWORDS: 09G2S steel, welded joints, external electromagnetic impact, longitudinal magnetic field, frequency, heat-affected zone, phase composition, microstructural parameters, microhardness

INTRODUCTION

To control the processes of melting electrode and base metals, as well as the process of weld pool metal crystallization, it is promising to use external magnetic fields affecting the drop, arc and liquid metal pool [1, 2]. In arc welding, longitudinal magnetic fields (LMF) and transverse magnetic fields (TMF) are used. In the first ones, an induction vector is parallel and in the second ones, it is perpendicular to the electrode and arc axis. Magnetic control has advantages over mechanical methods, because it is carried out without a direct contact of the control devices with the surfacing (welding) zone [3].

The use of LMF and TMF in arc surfacing and welding allows intensifying the process of melting the electrode, regulating the efficiency of the base metal penetration, influencing the process of the weld metal crystallization [4, 5]. There are many studies devoted to the analysis of the physics of the process of metal penetration under the external electromagnetic effect (EEE), distribution of pressure over the radius of the arc, movement of the electrode drop, flows of liquid metal in the welding pool, metal crystallization, as well as mechanisms of refining the structure of welds metal, including cluster theories of liquid metal crystallization [4, 6–8]. Namely, refinement of the metal structure leads to an increase in the level of metal strengthening (according to the Hall–Petch dependence [9]), and also will ensure its crack resistance [4, 10, 11]. Of course, the structural state, which is formed in the metal of welded joints under the impact of thermodeformation conditions of welding, affects their physical and mechanical properties.

As is known, the frequency of current significantly affects the nature of the power action of the electromagnetic field on the liquid metal [8]. With a decrease in the frequency, on the one hand, the electromagnetic interaction of the inductor with the melt deteriorates and on the other — the area of action of volumetric electromagnetic forces in a liquid metal expands.

If we change the polarity of switching windings with a certain frequency, then the direction of flows of molten metal will also change. This movement of a liquid pool in the real process of arc welding (surfacing) promotes refinement of metal grains in the process of its crystallization. When interacting along the *OX* axis with the component of current density in the pool metal, the induction component B_x of TMF generates an electromagnetic force that directs the flow of a liquid metal along the *OY* axis. Additionally, a vertical component of electromagnetic force (F_z) appears from the interaction of current density j_y in the side edges of the pool with the induction component B_x. When the polarity changes, a liquid metal is mixed across the pool axis [7].

The impact of alternating TMF leads to widening of the deposited beads [12, 13]. At a frequency $f = 50$ Hz, widening of the bead occurred in proportion to induction. However, it should be taken into account that TMF variable with a frequency of up to 1 Hz provides a wavy transverse movement of the bead axis, and to eliminate this drawback, it is necessary to use the TMF frequency from 2 Hz and higher.

In [14], it was studied how in arc welding the action of alternating magnetic fields with low frequencies affects the microhardness, parameters of microstructure of metal of 09G2S steel welded joints and the dimensions of the HAZ. However, the effect of the external electromagnetic field frequency on the structure of welded joints, generated in the welds and HAZ metal, has not been studied so far.

Therefore, the aim of this work was to find the regularities of influence of the frequency of the external electromagnetic field, namely LMF on the structural and phase composition, microhardness and microstructure of welded joints of low-alloy 09G2S steel.

MATERIAL AND PROCEDURES

To generate LMF, the procedure was used described in [9]. As a result of welding structural low-alloy 09G2S steel (4 mm thick) with the use of additive Sv-08A wire (3 mm diameter) (flux AN-348), the welded joints were produced using LMF on the following welding modes: current I = 360 A; arc voltage U = = 30–32 V; welding speed v = 30 m/h; reverse polarity; on a copper flux baching. The joint type is C4 (GOST 8713–78). Magnetic induction in the zone of the welding pool was 20–25 mT. The welded joints of two variants were produced at different frequency: f = 12 and f = 50 Hz. The results of experimental examinations of microstructure of welded joints produced with the use of LMF at the mentioned frequencies were further compared with the experimental data produced at f = 2 Hz [14].

Microstructure examinations were carried out using the methods of light microscopy (microscopes Neophot-32 and Versamet-2, Japan). The Vicker's hardness was measured in the hardness meter M-400 (Leco Company, USA) at a load of 0.1 kg. The morphology of ferrite (F) and perlite (P), grain sizes (D_g), width of crystallites (h_{cr}), thickness of ferritic interlayers (h_i) and microhardness (HV) were studied. In the welded joints, the base metal (BM), the weld metal, the fusion line (FL), the HAZ over the subzones: I — overheating (coarse grain); II — normalization (complete recrystallization); III — partial recrystallization; IV — recrystallization were studied.

RESULTS AND THEIR DISCUSSION

The structure of the base metal of 09G2S steel is ferritic-pearlitic at D_g(F) = 10–20 μm, D_g(P) = 40–80 μm and HV = 1650–1760 (Figure 1, *a*). The structure of weld metal is also ferritic-pearlitic (F–P), Figure 1, *b*–*d*. The width of the crystallites of the P-component at f = 2 and f = 12 Hz is almost the same (Figure 1, *c*, Table 1). However, at f = 50 Hz, h_{cr}(P) increases in average by 48 % (Figure 1, *d*) with a decrease in microhardness by 10 % (as compared to the mode f = 2 Hz) and by 17 % (as compared to the mode f = 12 Hz, Table 1). The F-component is finer with approximately the same size for all modes and lower microhardness than pearlitic one. An

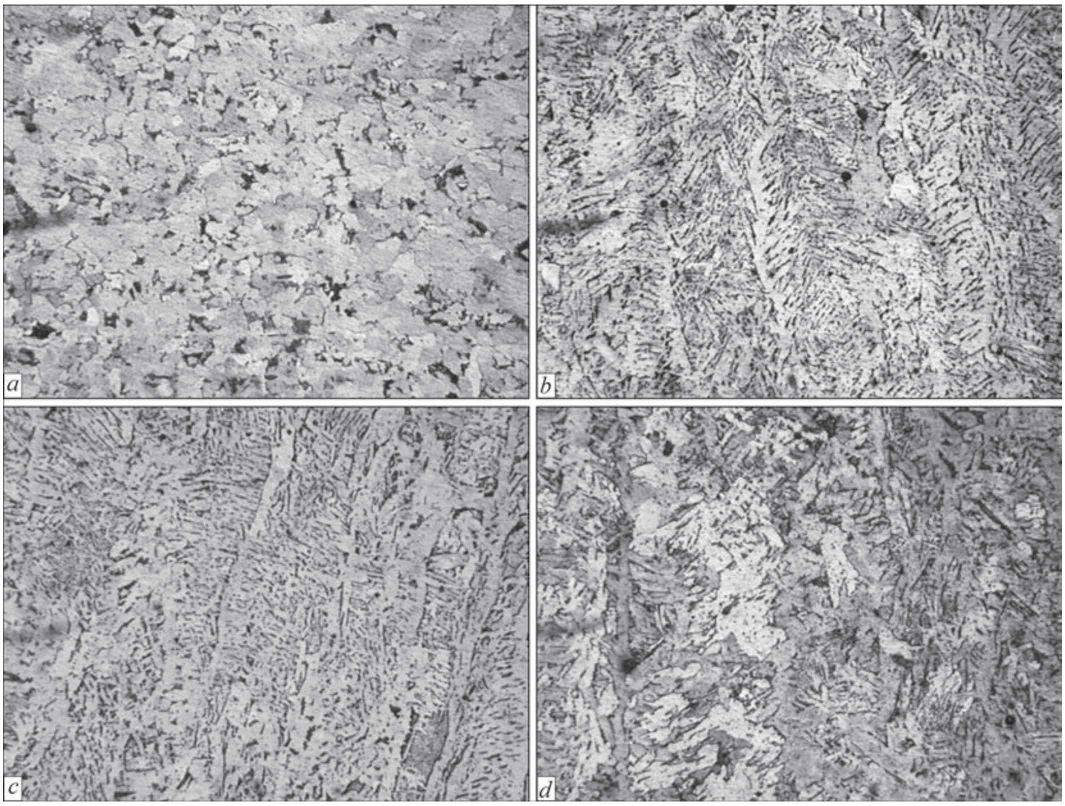

Figure 1. Microstructure (×250) of base metal (*a*) of 09G2S steel and welds (*b*–*d*) produced at different frequency: *b* — f = 2 Hz; *c* — 12; *d* — 50

increase in the width of crystallites at an increase in *f* correlates with the data of [14]. However, at *f* = 50, the structure is finer in average by 17 % as compared to the mode without the use of EEE [14].

Of course, an increase in the width of crystallites occurs at the stage of crystallization. If the axis of adjacent dendrite does not match the direction of a heat flow, it grows faster. In this case, the latent heat of melting, released into the surrounding liquid pool before the growing dendrites reduces the value of overcooling and will help to reduce the growth of adjacent ones [15]. Thus, a slow cooling of metal occurs.

In all cases, near the fusion line (FL), as compared to the weld metal, the width of crystallites is reduced (Figure 2, *a*, Table 1), which is associated with more intensive metal cooling in this subzone. In the specimen produced at *f* = 2 Hz near FL, a slight increase in *HV* (by 5 %, Table 1) is observed. At *f* = 50 Hz, in this zone, an average *HV* does not change, but the most uniform level of *HV* during the transition from the weld metal to LS is observed in the welded joint produced with the use of *f* = 12 Hz. It should be noted, that in all welded joints in the fusion line subzone, i.e., during the transition from the weld metal in I HAZ, single cold cracks are formed.

Studies of HAZ of specimens with the use of LMF at different frequency showed that in I HAZ of specimens on all modes a P-structure with ferrite interlayers is formed (Figure 2, *b*). In I HAZ of specimens at *f* = 12 and 50 Hz as compared to the specimen produced at *f* = 2 Hz, P-structure is refined (Table 2). The maximum grain size and the thickness of ferrite interlayers decrease, respectively, by 17 and 29 %. At the same time, the microstructure is slightly reduced — in average by 5 %. In II–IV HAZ in all modes, the structure is refined with the further uniform reduction in *HV* (Figure 2, *c*–*e*).

Table 1. Width of crystallites (h_{cr}, μm) and microhardness (*HV*, MPa) of metal of welded joints at different frequency (*f*) of LMF

Zone	h_{cr}(F)	h_{cr}(P)	*HV*(F)	*HV*(P)
	f = 2 Hz			
Weld	40–100	100–160	1760–1930	1990–2080
FL	20–40	60–140	1680–1990	1990–2280
f = 12 Hz				
Weld	20–100	80–160	1760–1930	2210
FL	20–60	60–140	1860	2060–2280
f = 50 Hz				
Weld	20–100	100–300	1650–1760	1810–1870
FL	50–100	60–200	1560–1700	1870

The studies of HAZ metal also revealed that during LMF, the frequency of the external electromagnetic field has an effect on the size of HAZ subzones (Table 2). In the studied welded joints at *f* = 12 and *f* = 50 Hz as compared to the welded joint produced at *f* = 2 Hz, the width (δ) of I HAZ increases by 25 and 8 %. This is associated with the more intensive movement of liquid

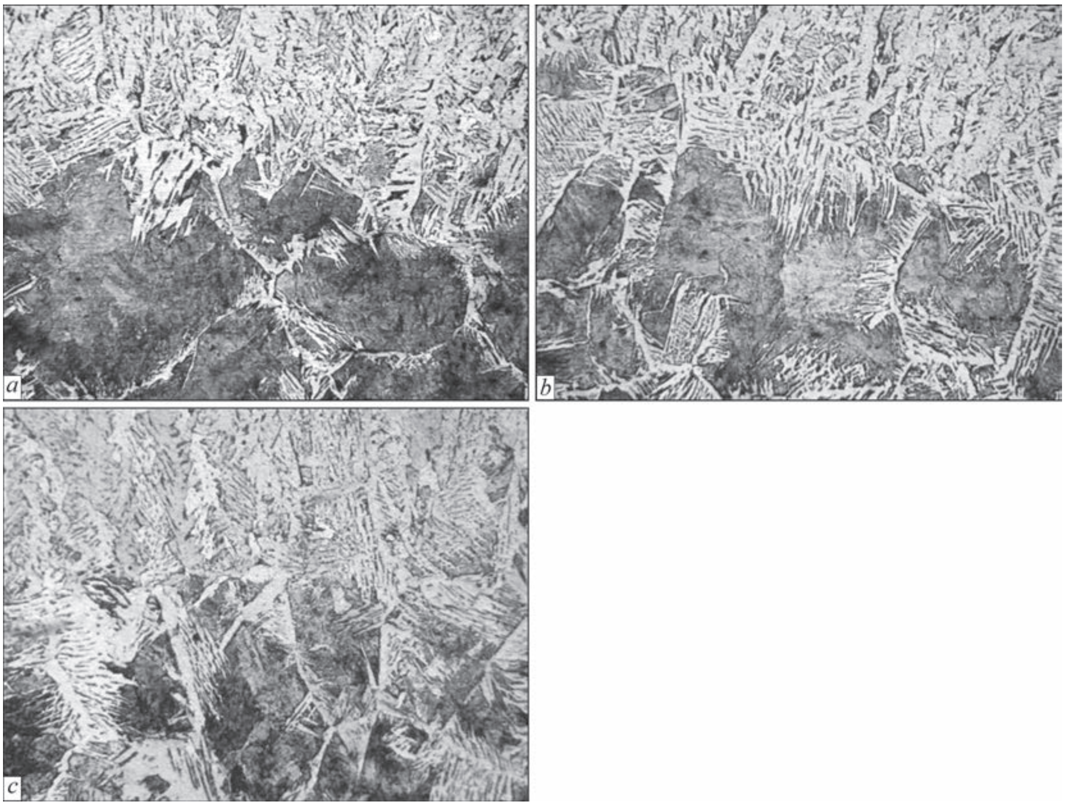

Figure 2. Microstructure (×250) of fusion line of 09G2S steel welded joints produced at different frequency: *a* — *f* = 2 Hz; *b* — 12; *c* — 50

Table 2. Width of HAZ subzones (δ, μm), grain size (D_g, μm) and microhardness (*HV*, MPa) of HAZ metal of welded joints at different frequency (*f*) of LMF

Zone	δ	D_g(F)h_i (F)*	D_g(P)	*HV*(F)	*HV*(P)
f = 2 Hz					
I HAZ	1300	30–70*	100–360	1810–1990*	2130–2210
II HAZ	1200	30–70	30–80	1870–1930	2060
III HAZ	1000	20–30	10–40	1810–1930	
IV HAZ	800	20–50	10–50	1870	
f = 12 Hz					
I HAZ	1650	20–50*	100–300	1760–1860*	2060
II HAZ	1000	50–100	30–100	1860	2060
III HAZ	1250	30–50	20–40	1700–1930	
IV HAZ	950	30–70	20–50	1650–1870	
f = 50 Hz					
I HAZ	1400	20–50*	140–300	1810–1870*	1890–2210
II HAZ	1500	20–80	50–100	1810–1870	2060
III HAZ	800	20–50	10–30	1760–1990	
IV HAZ	800	20–50	10–40	1600–1990	

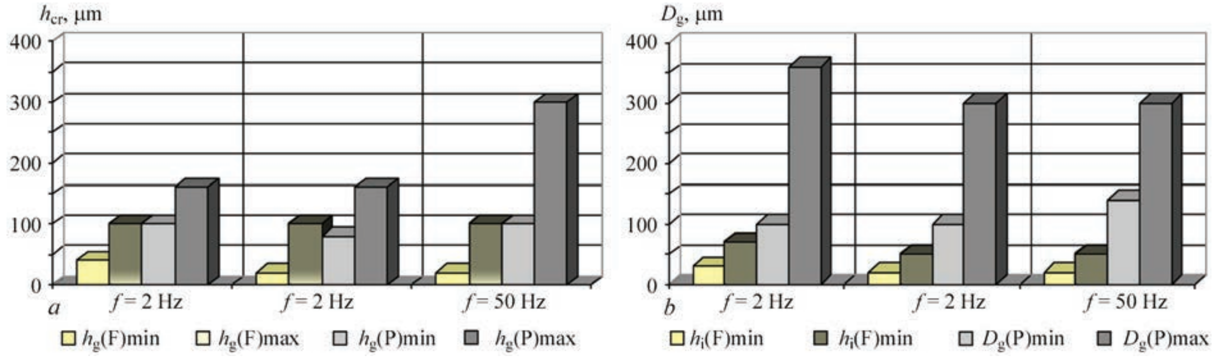

Figure 3. Change in structural parameters in the metal of 09G2S steel welded joints produced: with the use of LMF at different frequency *f*: *a* — width of crystallites (h_{cr}) in the weld metal; *b* — size of pearlite grains (D_g(P)) and thickness of ferrite interlayers (h_i(F)) in I HAZ

metal in the welding pool with an increase in *f* and, accordingly, with the thermal deformation conditions of structure formation in the HAZ metal.

An increase in the parameters of I HAZ, namely, in the overheating subzone can occur by changing the conditions of the process of melting and metal crystallization, namely, increasing the rate of heating liquid metal in the welding pool, as well as the temperature of its heating under the action of current pulses. Accordingly, this has an impact on an increase in the size of the overheating subzone (I HAZ) with an increase in the parameter *f*. The resulting temperature gradient contributes to an increase in the degree of overcooling and the rate of crystallization of the metal of the overheating subzone (I HAZ). This, in turn, leads to grain refinement of the structure in this subzone. In this case, an increase in width of I HAZ, which occurs with an increase in *f* will not negatively affect the properties of welded joints due to the refinement of the structure, as well as almost twice equalization of the gradient (Δδ) across the width of this zone — from Δδ = 600 μm (*f* = 2 Hz) to Δδ = 300 μm (*f* = 12 Hz) and Δδ = 400 μm (*f* = 50 Hz) (Table 2). This will provide a more uniform level of mechanical properties of the welded joint.

The studies revealed that the effect of the magnetic field frequency on structural changes is most noticeable in such subzones of welded joints as weld and I–II HAZ. The highest gradients in size of the grain structure are characteristic to the weld metal at *f* = 50 Hz (Figure 3, *a*) and metal of I HAZ at *f* = 2 Hz (Figure 3, *b*). At *f* = 12 Hz, the refinement of the grain structure is provided both in the weld metal as well as in the overheating subzone (I HAZ).

Thus, it was found how the effect of the external electromagnetic field, in particular, while using LMF, affects the sizes of HAZ, microstructure, microhardness of weld and HAZ metal in the welded joints of low-alloy 09G2S steel. The use of LMF at *f* = 12 Hz ensures refinement of grain structure in the weld metal and overheating subzone (I HAZ) as well as a uniform level of microhardness.

CONCLUSIONS

1. It was found that with an increase in the frequency of the electromagnetic field from *f* = 2 to 12 and

50 Hz, the microhardness and parameters of the microstructure of the weld metal and HAZ of 09G2S steel welded joints change. In this case, the phase composition of the base metal, the weld and HAZ metal is the same — ferritic-pearlitic.

2. At *f* = 50 Hz, in the weld metal, the width of the crystallites of the perlite component increases in average by 48 % with a decrease in microhardness by 10 % (as compared to the mode *f* = 2 Hz) and by 17 % (as compared to the mode *f* = 12 Hz). However, at *f* = 50, the structure is finer by an average of 17 % as compared to the mode without the use of EEE.

3. In the specimen produced at *f* = 2 Hz near FL, a slight increase in *HV* (by 5 %) is observed, and in I HAZ the most coarse grained structure is formed.

4. In I HAZ of the specimens at *f* = 12 and 50 Hz as compared to the mode *f* = 2 Hz, the structure is refined, respectively, by 17 and 29 %. Moreover, microhardness is reduced slightly — in average by 5 %.

5. Increase from *f* = 2 to 12 and 50 Hz leads to an increase in width of I HAZ in average by 25 and 8 %, but this will not negatively affect the properties of welded joints due to the structure refinement, as well as equalization of the gradient across the width of this zone from both sides of welds.

6. It was found that the mode at *f* = 12 Hz provides the most uniform level of microhardness both in the weld metal as well as over the subzones of HAZ and the formation of a fine-grained ferritic-pearlitic structure in the welded joint.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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