https://doi.org/10.37434/tpwj2022.05.01

INFLUENCE OF PULSED-ARC WELDING MODES ON THE STRUCTURE AND MECHANICAL PROPERTIES OF WELDS AND HAZ METAL OF WELDED JOINTS OF 30Kh2N2MDF STEEL

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ABSTRACT

The technological concept of welding high-strength steels with the yield strength over 1200 MPa is proposed and scientifically substantiated, which consists in combination of pulsed-arc MIG welding and application of a high-alloy wire of Cr–Ni–Mn alloying system. The structured information on the peculiarities of the thermal cycle and its influence on the structural transformations in HAZ and weld metal was obtained. The notion of the course of physical and metallurgical welding processes depending on basic parameters of standard and forced welding modes was developed. Their positive effect on mechanical properties of welded joints was established.

KEYWORDS: pulsed-arc welding, high-strength steels, properties, structure, heat-affected zone, austenitic welding material

INTRODUCTION

Recently, to implement projects on light armored tanks (LAT) of a new generation, modern heat-strengthened armored steels of high strength and hardness with a yield limit of over 1200 MPa are used. These are widely known domestic steel of 30Kh2NMDF grade [1] and steels of foreign production ARMSTAL 500, Miilux Protection 500, *HB* 500 MOD, RAMOR 500 and ARMOX 500S. To provide service properties, sheet rolled metal of mentioned steels of 6–20 mm thickness is hardened with the following low tempering. In the final heat-treated state in the structure of steel, tempering martensite is formed, due to which high values of static and dynamic strength are achieved, as well as high service characteristics. However, due to various reasons, technological properties are unsatisfactory for the successful use of high-performance processes associated with repeated heating, such as welding, surfacing, etc. A limited weldability is caused by both initial condition as well as high carbon content (> 0.3 %). Namely, the main problem of stationary arc welding (SAW) of armored steels is the change in the properties of metal in the heat-affected zone (HAZ) of welded joints [2]. The most significant changes occur both on the overheating area as well as on the area of HAZ tempering. Structural and phase transformations on the overheating area are characterized by an increase in the size of austenitic grain and development of a high-temperature chemical microheterogeneity and by lamellar martensite formation during the further cooling. This results in an increased risk of cold crack formation under the action of residual welding stresses. In turn, structural and phase transformations in the area of HAZ tempering do not have significant changes in morphology and grain sizes but lead to softening, which is caused by a whole number of factors, such as annihilation of dislocations, growth or dissolution of carbides, etc. [3, 4].

Another cause for the deteriorated weldability of armored steels is the formation of a brittle martensite interlayer or carbide ridge in the area of fusion, where the level of alloying is reduced to the level of the base metal [5].

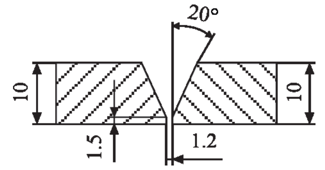
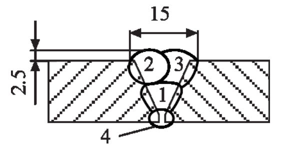
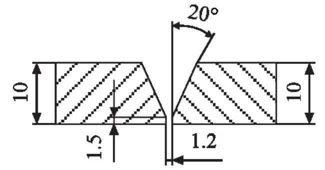
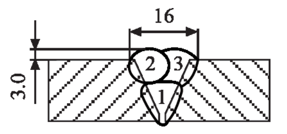
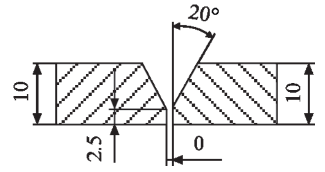
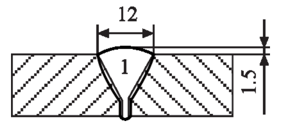
The mentioned features of formation of structure and properties of welded joints require performing welding in reduced modes, which leads to a decrease in the efficiency of manufacturing LAT products. This motivates a search for new welding technologies that will ensure a high efficiency and quality of products.

To solve this problem, we propose the following technological concept, which consists in applying the modern high-efficiency process of pulsed-arc welding (PAW).

The PAW process is qualitatively different from the traditional SAW in shielding gases. This is explained by the fact that in PAW the abilities to control the thermal cycle of welding and the processes of melting and electrode metal transfer in different spatial positions are expanded [6].

Since welding is characterized by physical and metallurgical processes that combine the concepts and a whole range of complex phenomena occurring

Table 1. Welded joint of 30Kh2N2MDF steel for investigations

Specimen number	Structural elements of preparation (mm, deg)	Welded joint
No. 1 Stationary process		
No. 2 PAW on a standard mode		
No. 3 PAW on a forced mode		

in molten metal and HAZ metal under the action of thermal cycle of welding (TCW), then the main factor that affects the entire course of the process is TCW [7–11]. It is characterized by such parameters as maximum temperature, heating and cooling rates, duration of metal staying above the specified temperatures at which heating occurs, melting of base metal and filler metal, formation of welding pool and metal of weld and HAZ, subsequent cooling and solidification as well as structural condition in different zones of welded joint is formed, technological strength (resistance to cold and hot crack formation), and physical and mechanical properties (strength, hardness, ductility, toughness, etc.) are provided. It is possible to control TCW by changing PAW modes, namely the main components: current and voltage of welding, frequency and duty cycle, welding speed.

In view of the abovementioned, in the work for the first time the study of the effect of PAW modes in MIG welding of the austenitic material on the structure of the weld and HAZ metal and the mechanical properties of the deposited metal of welded joints of steel 30Kh2N2MDF was performed.

PROCEDURE OF EXPERIMENT

To determine the effect of PAW modes on the structure, the mechanical properties of welded joints of armored steels of high hardness, the domestic armored steel of 30Kh2N2MDF grade of the following chemical composition was used, wt.%: 0.30 C, 1.1 Si, 0.73 Mn, 1.67 Cr, 2.28 Ni, 0.26 Mo, 0.21 V. In a hardened state (normalization and cooling in water) after a low-temperature tempering at 230 °C, the armored steel has ultimate strength and hardness at the level of 1500 and 5000 MPa respectively.

Considering that in the EWM Phoenix 501 plus power source during operation in a pulsed mode, welding parameters, namely, pulsed current I_{pulse}, pause current I_{pause}, frequency f and duty cycle δ are programmed by the manufacturer, to determine their impact on the structure and mechanical properties of the joints of steel of 30Kh2N2MDF grade in the selected welding modes, the average welding current (I_{av}) was used [12, 13]. To do that, welding of butt joints of the specimens of 71 steel of 10 mm thickness was performed. The dimensions of the structural elements of preparations of the specimens Nos 1–3 and welded joints are given in Table 1, and the modes of their welding are in Table 2. The welding of the specimens was performed by the wire of HORDA 307 grade (alloying system 08Kh20N9G7T) in the shielding mixture of gases 82 % Ar + 18 % CO_2. The electrode wire stickout in all cases was L_s = 15 mm. The general

Table 2. Method and modes of welding joints of 30Kh2N2MDF steel when performing investigations

Specimen number	Method of welding	Welding mode				Input energy, kJ/cm
		I_{av}, A	U_a, V	v_w, m/h	V_f, m/min	
1*	Stationary process — mechanized arc welding	180	24–26	18–21	5.6	7.5–6.4
2**	PAW on a standard mode	180	27	18–21	6.6	7.8–6.7
3**	PAW on a forced mode	300	29.4	24	10.4	10.6

Note. *Backup welding from the back surface of the specimen. **Without backup welding.

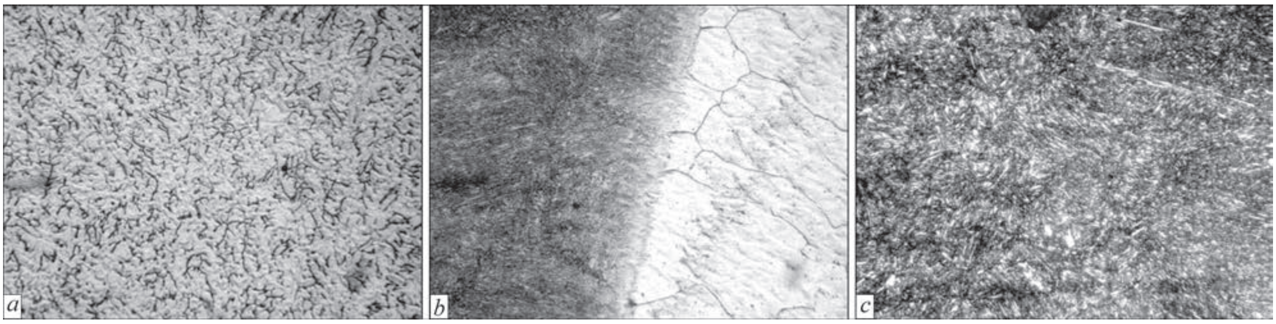


Figure 1. Microstructure (×500) of joint of 30Kh2N2MDF steel in mechanized welding on a stationary mode: *a* — weld; *b* — fusion line; *c* — coarse grain HAZ area

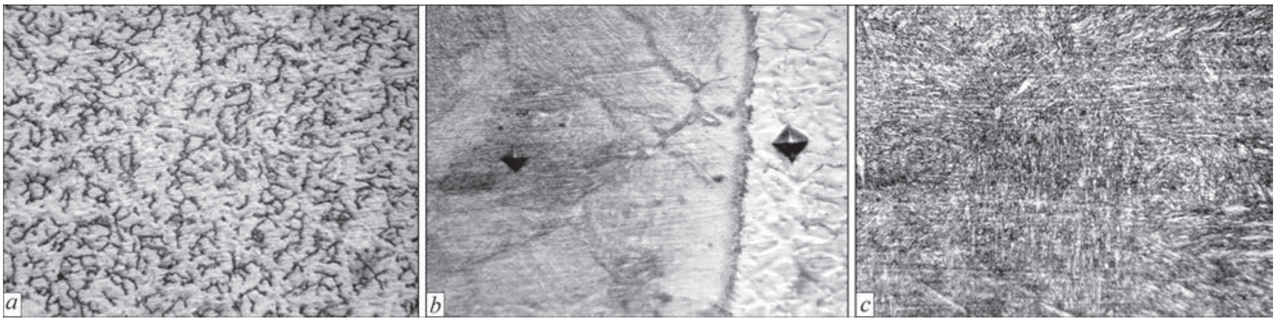


Figure 2. Microstructure (×500) of joint of 30Kh2N2MDF steel in PAW on a standard mode: *a* — weld; *b* — fusion line; *c* — coarse grain HAZ area

appearance of the specimens of steel 30Kh2N2MDF after PAW is shown in Figures 1 and 2.

The structure of welded joints was investigated by standard methods of optical metallography. Figures 3–5 show a typical microstructure of the weld metal, the fusion zone and areas of coarse grain of HAZ of welded joints of steel of 30Kh2N2MDF grade, produced by different methods of welding.

RESULTS AND DISCUSSION

It was found that the structure of deposited metal of welds of the specimens made by mechanized welding and PAW on a standard mode is austenitic with the microhardness ($HV_{0.1}$) 2540 and 2920 MPa respectively (Figure 1, *a*, Figure 2, *a* and Figure 4, *a*). The content of δ-ferrite in the deposited metal decreases from the weld root to the surface from 4 to 0.6 %. Microstructure of the weld metal of the specimen made by PAW on a forced mode (specimen No. 3) is significantly different from the microstructure of the metal of welds of the specimens Nos 1 and 2, namely, near austenite, martensite with a specific fraction of up to 19 % (Figure 3, *a*) appeared. This composite structure was obtained by mixing the weld metal with the base metal due to the effect of Marangoni convection [7]. This provided an increase in microhardness of the weld metal to ($HV_{0.1}$) 3450–4010 MPa. Along the fusion line, the areas of martensite are also observed (Figure 3, *b*, Figure 4, *b*).

The structure of the HAZ coarse grain area of the joint made by mechanized welding on a stationary mode (No. 1) consists of a mixture of lower bainite and martensite with the hardness ($HV_{0.1}$) 4100 MPa. During the transition to the pulsed mode (specimen No. 2), a mixture of bainite and martensite is also observed, but with a lower hardness value ($HV_{0.1}$) 4000 MPa). It is necessary to note that along the fusion line of the specimen No. 2, sometimes light pre-

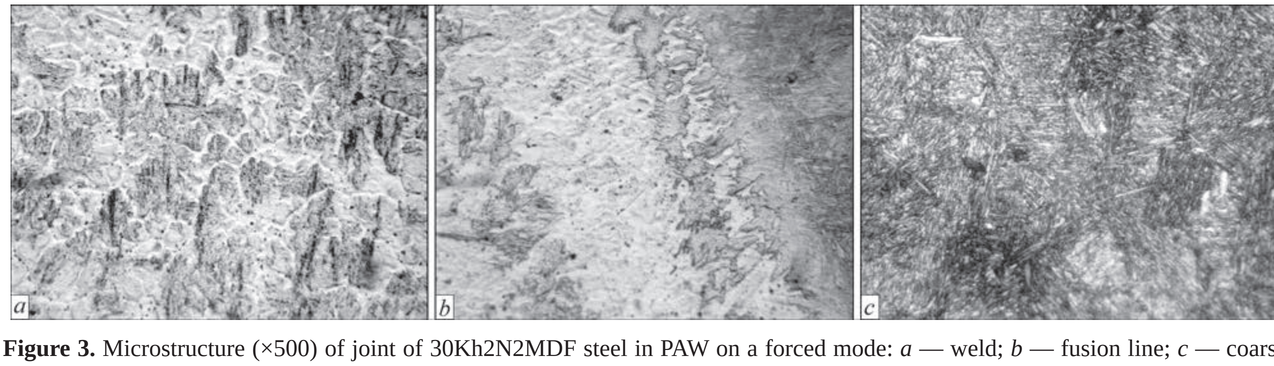


Figure 3. Microstructure (×500) of joint of 30Kh2N2MDF steel in PAW on a forced mode: *a* — weld; *b* — fusion line; *c* — coarse grain HAZ area

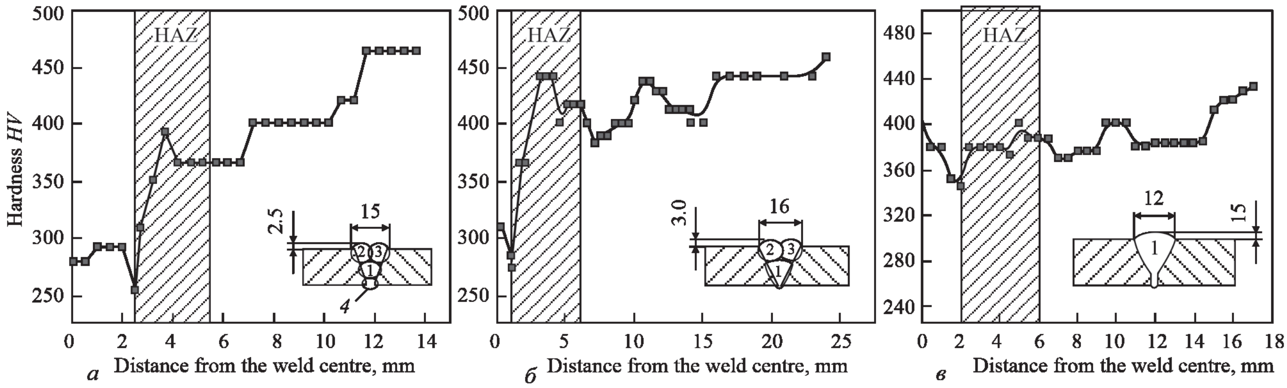


Figure 4. Distribution of hardness in the metal of welded joints of 30Kh2N2MDF steel: *a* — stationary mode; *b* — PAW on a standard mode; *c* — PAW on a forced mode

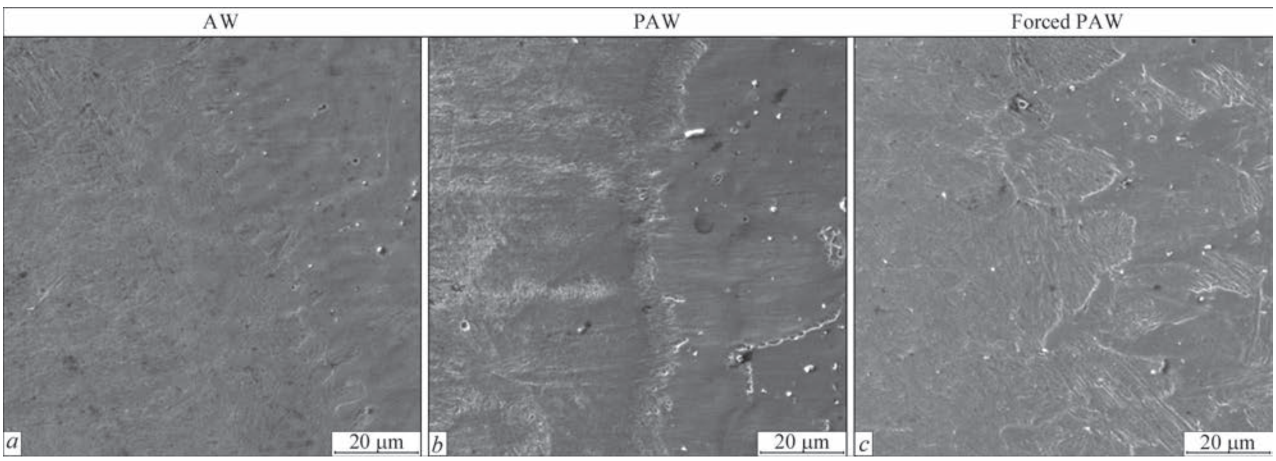


Figure 5. Microstructure of the fusion line in the area in the lower part of welded joint

cipitations can be seen, probably of the carbide phase. When moving from the area of HAZ coarse grain (specimen No. 2), the specific fraction of lower bainite increases, as a result of which, the hardness of this zone increases to 4420 MPa.

For the specimen produced on a forced mode in the metal of the HAZ coarse and fine grain area (No. 3), the structure of the mixture of bainite and martensite with the microhardness of components in the range of 3660–3800 MPa (Figure 4, *c*) is also observed. It should be noted that the base metal has a hardened martensitic structure with a microhardness of martensite of 4590–4640 MPa.

According to the changes in the structure, the mechanical properties of the deposited metal of welded joints, which were determined during tests at static tension and impact of standard specimens, respectively according to GOST 6996–66 and GOST 9454–78, are also changed in the structure. The generalized test results are given in Table 3.

Table 3. Mechanical properties of deposited weld metal of welded joints of 30Kh2N2MDF steel

Specimen number	σ_t, MPa	$\sigma_{0.2}$, MPa	δ_5, %	ψ, %	*KCU*, J/cm^2	
					20 °C	–40 °C
1	631	354	39	43	112	78
2	642	362	30	44	105	62
3	913	340	23	30	66	56

Since special attention in our studies is attracted by the structure formed on the fusion line, which subsequently determines the structurally independent mechanical properties of the whole welded joint, to perform a detailed study, the capabilities of optical microscopy with ×1000 resolution are not sufficient. In this regard, scanning microscopy was additionally used. For the analysis, three areas on the fusion line were selected: in the lower, middle and upper part of the welded joint. For element analysis, a linear scanning of 1 mm length perpendicular to the fusion line was performed. This allowed analyzing the distribution of chemical elements of the main alloying system, namely Cr, Ni, Mn and revealing the features of their redistribution between the weld and the base metal.

While studying fusion line at a high resolution capacity (at magnifications ×2000, Figures 5–7), it was revealed that in stationary arc welding, a toothed morphology of the shore on the interface austenitic weld — base metal is formed.

In the weld root, during PAW a smooth transition from austenitic material to alloyed one is formed. And on a forced mode of PAW, the morphology changes

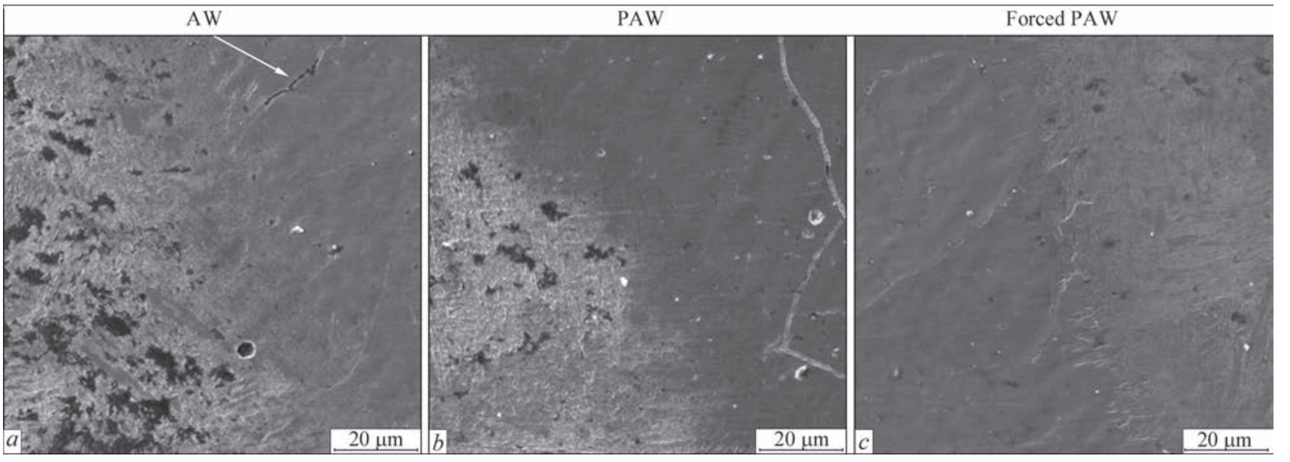


Figure 6. Microstructure of fusion line in the area in the middle part of welded joint

radically, a qualitative mixing of austenitic and base metal with the formation of mixed austenitic-martensitic structure is observed. In the middle of the weld, for PAW and a forced mode, the situation is the same as in the root, and for AW, the morphology of the shores changes, namely, a wide area of the martensitic-bainitic structure appears, and on the side of the austenitic weld, a discontinuity with a length of about 15 μm appears, which can potentially be the nucleus of a cold crack. In the upper part of the weld at the fusion line, a smooth transition from one to another material is also observed for PAW and a forced mode, and for AW an area with pronounced carbide inclusions is present.

All the mentioned changes in the structure and chemical inhomogeneities of the blocks and grains, caused by the change in the cooling rate, exert a significant influence on the properties of the weld metal in general, including such indices as impact toughness, etc. As a rule, the fracture of metals, including brittle one, occurs only after a certain amount of plastic deformation. When encountering an obstacle in the sliding plane, for example, slag inclusions, block boundary, boundary intersection of three grains, a series of *n*-dislocations of the same sign is formed, which exerts a pressure on this obstacle that is *n*-times higher than the applied stress. This growing stress concentration can lead to one of two consequences: the further propagation of a shear into the neighboring grain or the formation of a microcrack, which is in a good agreement with the results of microscopic analysis obtained in the work.

The analysis of the redistribution of chemical elements along the fusion line made it possible to find that on a forced mode of PAW, an active mass transfer is observed, caused by mixing in the transition zone austenitic weld-base metal, which, as was mentioned earlier, is predetermined by the Marangoni effect.

The change in the content of the alloying element in the fusion zone of these dissimilar materials depends on the method of welding and the heat input of welding. The type of fusion of dissimilar steels depends on the welding mode. Its change causes a redistribution of the elements included in the composition of the welded metal, especially those, having a high diffusion coefficient. In the modes that increase the time when the fusion zone of the welded metal stays in the region of high temperatures, diffusion processes intensify in it, as a result of which an accumulation of elements occur, that form easily melting or brittle

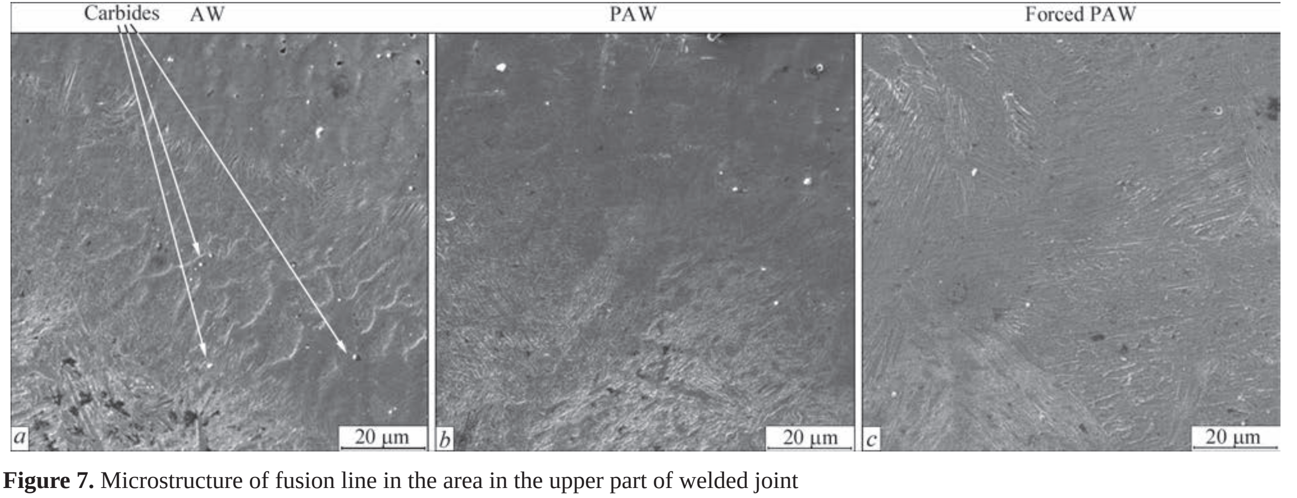


Figure 7. Microstructure of fusion line in the area in the upper part of welded joint

compounds at the grain boundaries. The presence of such compounds at the grain boundaries leads to the formation of an alloy from wedging of the deposited metal into the base one in the form of islands/peninsulas. This wedging is repeated so often that the fusion zone acquires the appearance of a fringe. Microscopic studies also confirm that in this case the fusion boundary acquires a wavy shape.

Fusion of dissimilar steels with wedging of the weld metal into the base metal can also occur in this case, if the latter has a chemical composition, at which interlayers are formed between the grains prone to embrittlement. The stresses arising during welding cause cracks in these interlayers, into which the liquid metal of the welding pool penetrates during further formation of the welded joint, and in the case when the metal does not flow into, they are the nucleus of cold cracks.

It can be assumed that the formation of islands and peninsulas in the fusion zone is determined by the conditions of mixing the liquid metal of the welding pool in a thin layer directly adjacent to the fusion boundary. The islands and peninsulas are formed if the liquid metal, for some reason, is not sufficiently mixed. This is evidenced by the fact that the fusion border of the base and deposited metal directly near the islands has a zigzag shape, where the «teeth» of the base metal, penetrating into the fused metal, lose the sharpness of their contours as they blur. In the case of good mixing, the borders acquire clear outlines. A number of islands observed in the fusion zone, as well as the probability of their appearance, depend on the mode and method of welding.

As we can see, at the transition from stationary arc welding to a pulsed mode and an increase in the current to 300 A lead to an increase in the yield limit of the deposited metal by up to 30 %, while maintaining a sufficiently high level of plastic and impact toughness characteristics at low temperatures. Such effect can be explained by more intense mixing of electrode and base metals in the welding pool and a specific form of «keyhole» penetration in pulsed-arc welding on forced modes (effect of Marangoni convection).

The microstructure of the weld metal of the specimens produced in the stationary and pulsed modes (Nos 1, 2) is austenitic with a hardness of ($HV_{0.1}$) 254 and ($HV_{0.1}$) 292 MPa, respectively. The content of δ-ferrite decreases from the weld root to the surface from 4 to 0.6 %. The microstructure of the weld metal of the specimen produced on a forced mode (No. 3) is significantly different from the microstructure of the weld metal of the specimens No. 1 and 2, namely, in the structure of the weld metal of the specimen No. 3, near austenite, martensite appeared with a specific fraction of up to 19 %. This composite structure was obtained due to mixing of the weld metal with the base metal provided by the effect of Marangoni convection. This allowed increasing the hardness of the weld metal to ($HV_{0.1}$) 345–401 MPa. Along the fusion line, areas of martensite are also observed.

Thus, it was shown that applying pulsed-arc welding on a forced mode, it is possible to obtain a composite austenitic-martensitic structure of the weld metal, a minimum scattering of hardness values in the HAZ metal and during transition to the base metal, which provides a significant improvement in the mechanical properties of the welded joint as a whole.

CONCLUSIONS

The impact of pulsed-arc welding modes on the structure, mechanical properties of welded joints of high hardness armored steels, and on their resistance to the formation of cold and hot cracks was studied. The following was established.

1. During pulsed-arc welding in stationary mode (average current is 180 A) using a high-alloy wire of the alloying system 08Kh20N9G7T, the structure of the deposited metal, as compared to conventional mechanized welding, almost does not change and remains austenitic with a microhardness of up to ($HV_{0.1}$) 2920 MPa. The content of δ-ferrite in the deposited metal decreases from the weld root to the surface from 4 to 0.6 %.

2. In pulsed-arc welding on a forced mode (average current is 300 A), in the deposited metal significant changes occur, namely, in the austenite structure martensite areas are formed, their total specific fraction is up to 19 %. This promotes an increase in the microhardness of the deposited metal to($HV_{0.1}$) 3450–4010 MPa. This composite structure was obtained due to intensive mixing of the weld metal with the base metal due to the effect of Marangoni convection. In the near-weld metal of the HAZ joints on this welding mode, the microhardness decreases from 4100 to 3800 MPa.

3. In accordance with changes in the structure, the mechanical properties of the deposited metal of welded joints of armored steels also change. In pulsed-arc welding on a forced mode, the tensile strength of the deposited metal increases to 30 % while maintaining a sufficiently high level of plastic and impact toughness characteristics.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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SUGGESTED CITATION

O.A. Gaivoronskyi, V.D. Poznyakov, Yu.V. Demchenko, A.M. Denysenko, A.V. Zavdoveev, V.A. Kostin, T.G. Solomiychuk (2022) Influence of pulsed-arc welding modes on the structure and mechanical properties of welds and HAZ metal of welded joints of 30Kh2N2MDF steel. *The Paton Welding J.*, **5**, 3–9.

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Received: 24.02.2022
Accepted: 08.08.2022