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Effect of Heat Input Pulse on the Structure and Properties of Welded Joints of Steels Ferritic-Pearlitic Class, Operating Under Low-Frequency Temperature-Force Loading*

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Abstract. We have investigated the influence of the modes of adaptive pulse-arc welding and surfacing on the structure and physical-mechanical properties of welded joints of steel 09Mn2Si and the surfaced composition of this steel coated with modified powder material of chromium carbide with the submicrocrystalline structure. It is shown that the pulsed mode of welding and surfacing can improve the homogeneity of the structure of the welded joint of steel and surfaced coating and reduce the grain size of metals in both of them. Structural changes lead to the increase in ductility and toughness of the weld metal.

Introduction

The problem of increasing the serviceability of the products containing welded joints and surfaced coatings is quite urgent. One of the most effective trends of enhancing the performance characteristics of high-duty constructions is improvement of the welding procedure and surfacing due to application of new welding materials, modified by multiphase structural compositions [1-10], and methods of adaptive pulsed-arc welding and surfacing that provide the opportunity to control the nature of micrometallurgical processes behavior due to the pulsed modification of power mode parameters [11-15]. At the same time owing to a programmable input of heat into the area of a welded joint, control of the melting processes and transfer of every droplet of the electrode metal, it is possible to obtain a disperse structure in weld metals, coatings and their heat-affected zones in the areas of permanent joints of engineering systems. This allows a significant decrease in the degree of residual strains and enhancement of product operational reliability.

When surfacing carbon steel the hardening occurs owing to formation of a new surface layer. The surface properties after surfacing the steel depend on the type of alloying elements determining the phase constitution, boundaries of phase transitions and mechanical properties. Hard alloys possess the properties determined by the chemical composition (carbides, borides, nitrides). One of the methods of increasing the strength of steel is grain refining. During this process, the steel yield strength increases and simultaneously the cold-shortness threshold decreases. The process-dependent parameters of surfacing as well as the quantity and the size of alloying elements influence the structure and properties of the weld metal. When the mode of surfacing is changed, the process of material melting and chemical homogeneity of the pad weld. In particular, the wear resistance and impact resistance of the hardened parts are influenced by the fact of retaining of the strengthening phases (carbides, borides, nitrides) and their form, sizes, and disposition in a matrix material in the process of surfacing. The matrix material is characterized by the degree of fixedness of solid inclusions and the capability to take alternating loads. The resistance of the matrix material to different loads depends on the operational conditions of the product, nature of load actions, and operating environment.

The object of the paper:

Enhancement of the structure and properties of weld metals and surfaced coatings by means of application of the methods of pulsed welding procedure and surfacing during modification of the melted metal by composite powder materials possessing submicrocrystalline structure.

Materials and research methodology

In the paper samples of weld joints and surfaced coatings of steel 09Mn2Si have been studied. Welding and surfacing were conducted by means of the electrodes of UONI 13/55 model, FEB-315 “MAGMA” power supply with control panel “Pulse” for realization of the pulsed-arc welding process. The welding procedure and surfacing were conducted with the use of direct current (DCW) and welding with current modulation (CMW) which is known as adaptive pulsed-arc method. The registration of the parameters of welding and surfacing processes was conducted by means of apparatus AWR-224 MD. Welded joints were subjected to radiographic inspection by X-ray unit “PION-2M” according to GOST 7512-82 methodology. The macrostructure was studied by means of the optical microscope. The microstructure was investigated by means of the optical microscope NEOPHOT-21. The measurements of microhardness of welded joints and surfaced coatings were conducted with the use of the microhardness tester Leika. The presence of chromium carbides was determined by the X-ray structural analysis on plant DRON 3M. Chromium distribution in the composition “surfaced coating– steel base (09Mn2Si)” was determined by means of X-ray microanalysis (XRMA). Bending impact tests were conducted according to GOST 1497-84 using testing machine UMM-5. The studies of fatigue crack life were carried out according to GOST 5264-80. The cycling tests of samples were conducted with the use of machine INSTRON 8802 at frequency of cycling equal to 5 kHz. Magnetic characteristics of different areas of welded joints of steel 09Mn2Si were registered by means of the complex Remagraph C-500.

The results of the experiment

In the initial state the base metal – steel 09Mn2Si possesses hardness equal to ~250 HV0.05, welding material hardness which is ~ 270 -300 HV0.05, weld-adjacent zone (WAZ) hardness equal to - 210-230 HV0.05. The distribution of microhardness in the studied samples corresponds to the twenty-percent criterion. Steel 09Mn2Si in the initial state has a lineage ferritic-pearlitic structure with grain sizes equal to ~10 μm, which corresponds to the 10th grain size index. The grain size of WAZ exceeds the size of initial grain, which is connected to metal overheating during the welding process. During welding with the use of direct current the area with the enlarged grain size is wider than it is during welding using current modulation which allows pointing out high heat inputs and long-term thermal influence of the glowing arc [2]. Metallographic studies of the welded joints revealed refining of the structural constituents of WAZ material ~1,5 times less after CMW. It is explained by the peculiarities of the pulsed mode of welding when an intensive mixture of the melt with formation of new crystallization centers occurs. After CMW the width of heat-affected zone is less, and there is not any grain growth in it, which positively influences the quality of the weld joint in general. The ferrite-carbide structure of the weld after DCW resembles Widmanstätten structure (Fig. 1, a). However, there is not any observable reduction in strength properties, which is characteristic for steel having the same structure. In the central part of the weld coarse bainite grains with ferrite grains on the boundaries are typical for the structure.

The grain size after DCW is up to ~1,5 times greater than after CMW (Fig. 2), which is due to the fact that the structure of the root and filling pad of the weld after crystallization is subjected to reheating during subsequent layup.

As a result of this heating recrystallization (normalization) takes place. During DCW the heating temperature of the weld pads is higher than the temperature of the phase recrystallization, and, as a consequence, the grain growth occurs.

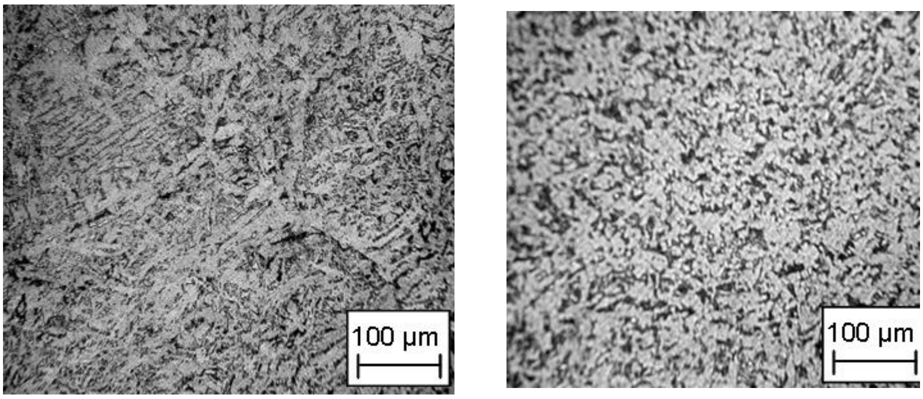

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Figure 1. Microstructure of the weld metal after welding: a) DCW; b) CMW

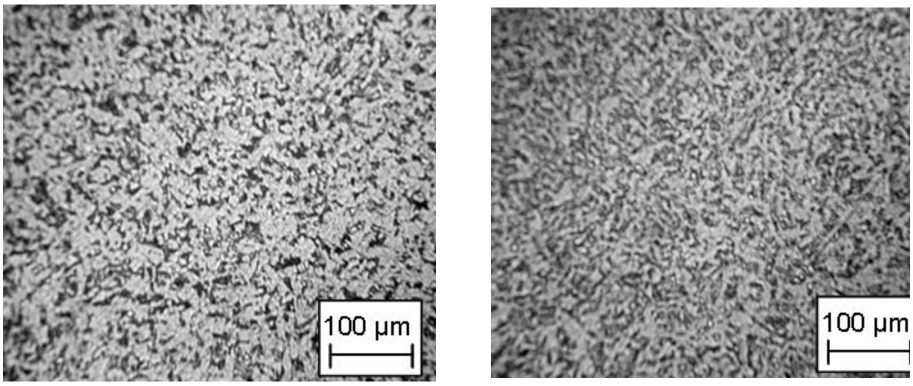

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Figure 2. WAZ microstructure of the weld at different modes of welding: a) DCW; b) CMW

During CMW the secondary heating takes place at the temperature close to that of polymorphic transformation of steel which contributes to structure refining. The increase in hardening in the weld zone correlates with the results of the mechanical tests for uniaxial tension. The properties of materials of the weld joint after CMW are given in table 1.

Table 1. Mechanical and magnetic properties of materials

Material	$\sigma_{0.2}$, MPa	σ_B, MPa	δ, %	ψ, %	$\sigma_{0.2}/\sigma_B$	H_c, A/sm	B_r, T	μ_{max}	M_{max}, T
WAZ	340	450	15	44	0,76	4,37	1,28	1430	2,13
Weld seam	375	480	11	51	0,78	5,95	1,00	824	2,23

It is important to note that the index of ratio $\sigma_{0.2}/\sigma_B$, which growth characterizes the reduction in the ductility of metal, for the weld material is lower than for the base metal and WAZ. WAZ material possesses maximum values of the ratio $\sigma_{0.2}/\sigma_B$, which indicates an increased probability of brittle structure taking place in this zone. A weld joint obtained by means of CMW is the most equal in strength: the change in the ratio of strength properties from zone to zone does not exceed 2,5 %. Samples of weld joints after tests at room temperature have plastic fracture in a zone of the rupture area, and at negative temperature - there is brittle fracture. The tests have shown that the impact strength of CMW metal of all the samples mentioned above is higher than it is in the base metal. Maximum impact strength (KCV=1,05 MJ/m^2) is reached on samples belonging to WAZ subjected to CMW, and the lowest values are obtained when KCV=0,86 MJ/m^2 with the use of DCW. Fractures of all tested samples have viscous (fibrous) structure. Fractograms of sample fractures after tests at room temperature justify that the fracture is tough with the pit size of 10-40 μm (Fig. 3).

This pattern is observed both in the case of the base metal and in the heat-affected zone. The parameter values of dynamic fracture strength correlate with the magnitude of toughness very well. They allow best revealing the advantages of WAZ metal after CMW in resistance to brittle fracture of metal in comparison to DCW mode. The values of the work on fracture propagation, obtained using the results of processing of impact diagrams, are 2-5 times higher than the values of work of fracture initiation for all tested samples that justifies the presence of significant structural strength margins in metal of different areas of weld.

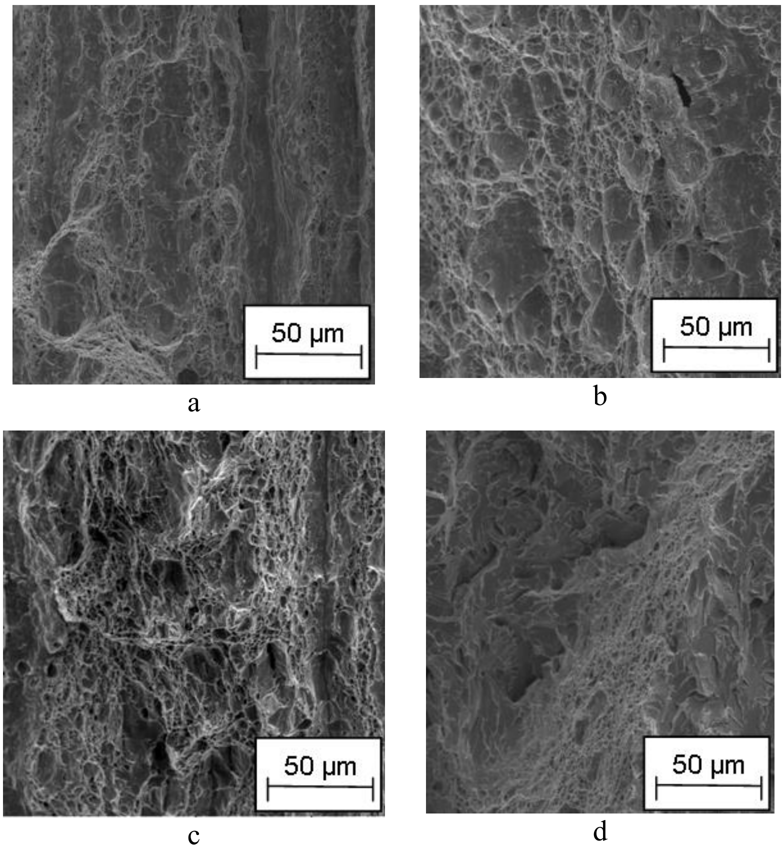

Figure 3. Fractographs of sample fractures after testing at the following temperatures: 1) 20 °C, base metal (a) and WAZ (b), 2) - 60 °C, base metal (c) and WAZ (d).

It is important to note that with the decrease in testing temperature up to –60°C the impact characteristics of the base metal change insignificantly. WAZ metal after CMW obtains a higher level of impact strength characteristics at -60°C. Sample fracture mechanism obtained by means of DCW after tests at a temperature of –60 °C for base metal is viscous and dimple, and for the weld adjacent zone it is quasi-spalling. However, for samples after CMW the rupture mechanism of the heat-affected zone is mixed: there are areas containing viscous dimple fracture. This fact indicates that this kind of welding mode decreases the risk of fracture occurrence in the weld adjacent zone.

The conducted comparative tests have revealed the advantages of fatigue crack growth in the field of stress intensity factor exceeding 20 MPa $\cdot m^{1/2}$ of the WAZ metal of the welded joint obtained by CMW.

The studies of magnetic properties of the base metal, weld materials and WAZ have shown that in the initial state the coercive force of the base metal is less than that of the metals of other zones. Increased magnetic hardness of WAZ metal and weld is conditioned by a greater number of alloying elements in the electrode material as well as by the presence of the dispersed bainite in their structure and an increased level of internal stresses in weld metals and WAZ metals. The magnetic texture of stresses (induced magnetic anisotropy) is formed [3]. If material magnetostriction and external stresses have like signs we can observe the preferred orientation of magnetic domains in the direction of the applied load, and therefore there is a decrease in values of coercive force, increase in magnetic permeability and residual induction along the axis of elongation.

When ready-made carbide compounds are introduced into the coating formed during surfacing, it is possible to obtain the structure of weld metal with strengthening carbide phase located in the immediate region of the grain. Powder materials on the basis of submicrocrystalline particles of chromium carbides were applied as modifying mixtures. For implementation of surface hardening different schemes of introduction of powder compositions containing submicrodimensional-hardening particles have been developed to apply coatings.

Alloying with ready-made compounds significantly simplifies the adjustment of alloy matrix structure, as in this case redistribution of alloying elements between the high hardness phase and matrix slows down. In the alloy structure there are fine carbide impurities spread all over the coating volume. In the process of coating the embedment of such phases in the metal matrix leads to formation of dispersion strengthened pads and enhancement of physical-mechanical and service properties of the obtained materials. The study and optimization of crystallization processes, temperature control of the melt on the account of the introduction of the dispersed refractory compounds, modifying coating material including refinement of their structure and enhancement of their properties, into the composition of the surfacing materials, all of which allows optimization of the technology of surface coating.

Hardening is achieved through a directed high energetic and modifying influence of dispersed high melting compounds on the structure, physical-mechanical and auxiliary properties of coatings made of metals and alloys applied by the surfacing methods. During pulsed-arc surfacing as a result of influence of repetitive live pressure of the arc, while surfaced coating is being formed, the metal of the welding bath carries out reciprocal motions owing to periodic power influence of the arc with modulation frequency of current. This kind of surfacing process behavior provides repetitive cycling recurrence of physical processes at the stages of formation of weld bath and crystallization of the coating metal out of the melt and enables its dynamic stirring. Such stirring of the melt contributes to levelling its heat content and provides setting of the required quantity of the melted metal under the arc by time of starting of current pulse operation thus contributing to the reduction of the weld penetration. Periodic motion of the metal in melt enables levelling of its heat content and more uniform distribution of alloying elements throughout the whole volume of the melted metal.

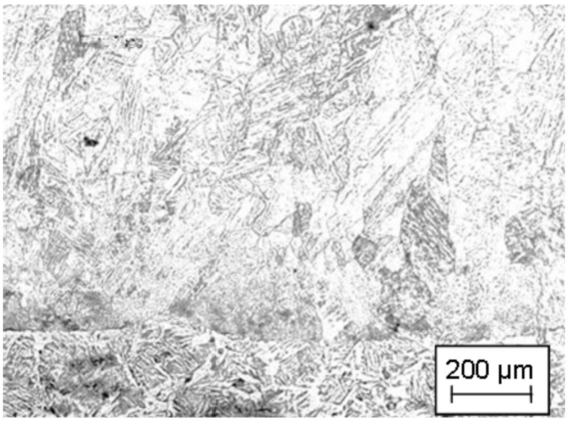

Figure 4. The structure of the interface region "surfaced coating – steel base (09Mn2Si)". (Coating - top.).

The interface region "surfaced coating – steel base (09Mn2Si)" and the traces of microhardness imprints after pulsed-arc weld surfacing are shown in figures 4 and 5. Chromium distribution on the boundary of interface "surfaced coating – steel base (09Mn2Si)" after pulsed-arc weld surfacing obtained by means of XRMA and diffractogram of surfacing are shown in figure 6. The fact of chromium distribution is evidence of a more significant content of this element in the surfaced pads.

Thus, a new complex approach to improvement of properties of welded joints and surfaced coatings of the products made of low-carbon steel 09Mn2Si by means of application of the method of adding materials modification using superdispersed high melting particles and pulsed technology has been proposed.

The use of the consumables in the batch – in electrodes and wires of the components containing microalloying additives allows influence on the structure and properties of the molded metal – the welded joint and surfaced coating. During modification the structure of weld metal is refined and, as a consequence, physical-mechanical properties and performance characteristics are improved.

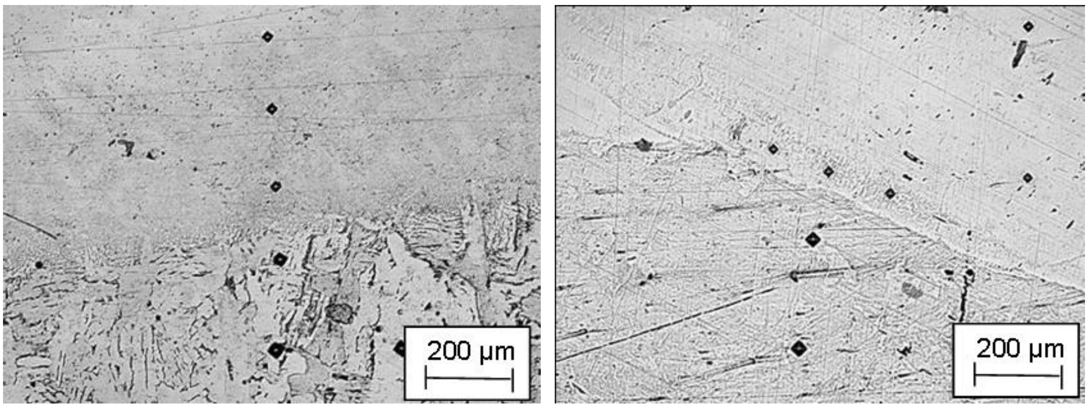

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Figure 5. Traces of microhardness imprints in the interface region coating – base. The base has been etched (a) and slightly etched (b). The coating (top) has not been etched

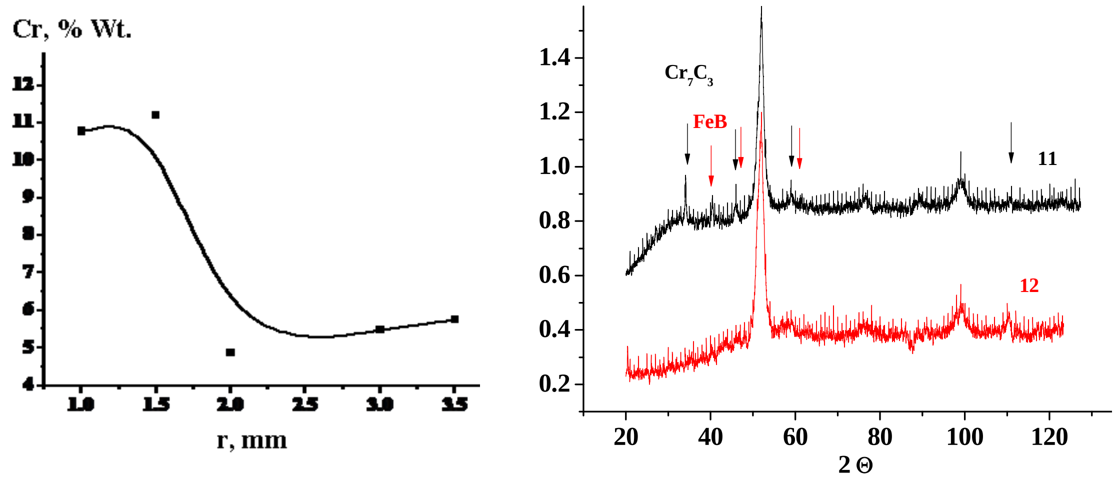

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Figure 6. Chromium distribution at the interface "surfaced coating - steel base (09Mn2Si)" (a) and the diffractogram of coating (b)

The novelty of the approach under development is in providing of the continuous monitoring over metallurgical processes at the stage of formation of permanent joints by means of complex application of new additive materials, modified by multiphase compositions, application of the equipment and technologies of adaptive pulsed-arc welding and surfacing, which allows control over the processes of melting and transfer of each drop of electrode metal by means of programmable heat input into the area of welded joint, and, as a consequence, providing formation of the dispersed structures in the areas of welded joints of technical systems, which leads to an increased resistance of these joints to delayed and brittle fracture. This allows a substantial decrease in the degree of the residual deformations in the areas of structural heterogeneity and, as a consequence, enhancement in operational reliability of the products.

Application of the pulsed mode of welding provides significant refinement of the structure of weld metal and HAZ, which is most subjected to structural changes, owing to adjustable heat input, as a result of which there is plummeting in microhardness and strength in this zone and thereby the degree of softening in the fusion zone of the weld is reduced. If combined these changes provide the reduction in postwelding deformations and an increase in toughness of welded joints.

Conclusions

1. Application of the method of pulsed-arc welding of low-carbon steel 09Mn2Si allows formation of welded joints with more fine-grained structure in weld metals and HAZ, as well as with uniform distribution of hardness in them in comparison with compounds obtained by means of arc welding using direct current.
2. The result of mechanical tests for uniaxial tension correlates with hardness increase in the weld zone. The maximum values of the ratio of yield and tensile strengths belong to WAZ material. The most full-strength weld is that obtained by CMW technology, for which the change in the ratio of strength properties of separate zones of the welded joint does not exceed 2,5%.
3. The maximum value of toughness at room and negative temperatures of tests (-60°C) is reached after application of CMW. The values of the parameter of dynamic fracture toughness properly correlate with the value of toughness, which allows revealing neatly the advantages in brittle fracture resistance of WAZ metal after CMW.
4. Comparative tests have revealed the advantages of the fatigue crack growth of WAZ metal of the welded joint obtained by CMW in comparison with the base metal. It has been established

that at room temperature in a low-cycle region the durability of weld metal of welded joints of 09Mn2Si steel obtained by means of CMW is higher than those obtained by means of DCW.

5. It has been found that the analysis of field dependencies of differential magnetic permeability allows receiving data on the condition of separate components of the welded joint. The obtained characteristics can be applied for estimation of the degree of deformation at the stage of elastic stresses in the products during operation.

6. Application of the method of pulsed-arc surfacing along with modification of the melted metal with composite powder material of chromium carbide, which possesses a submicrocrystalline structure, allows obtaining such dispersed strengthening phase in the coating of low-carbon 09Mn2Si steel.

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