WELDING FROM ONE SIDE OF CLAD PIPING OF NUCLEAR POWER PLANTS

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Regularities of structure formation in bimetal material welded joints are generalized. Causes for deterioration of toughness, ductility and technological strength of weld metal are considered. Technological measures to ensure the required service properties and crack resistance of weld metal are specified. Initial data are determined to develop the basic process of welding from one side the NPP piping from clad sheets.

Keywords: *arc welding, clad steels, welded joints, brittleness, cracks, carbon diffusion, brittle interlayers, welding technologies*

Clad pipes in critical structures are used, in particular, in the main circulating pipeline of NPPs. The main metal of the pipe is higher-strength low-alloyed steel which is coated with corrosion-resistant austenitic steel inside.

At replacement of steam generators it is necessary to make a butt joint of the main circulating pipeline and steam generator nozzle. Abutted elements are made from 10GN2MFA steel. Pipe inner diameter is 850 mm at 70 mm thickness.

In keeping with the standard technology, the edges of the made joints of low-alloyed steel have V-shaped groove opening outside; 10 mm wide cladding layer has been removed on each edge (Figure 1). Cladding removal is associated with elimination of the possibility of cracking at austenite metal penetration into the low-alloyed pearlitic root weld. Such joints are made in two stages. First heat-resistant steel 10GN2MFA is welded across the entire thickness from the outside and NDT of the joint is performed as follows: 100 % X-ray structural (RI), 100 % ultrasonic (UT), 100 % liquid-penetrant inspection (LPI). Then deposition of a double anticorrosion layer is performed in the section of milling the pipe inner surface. After deposition, the deposited layer reinforcement is ground flush with the cladding surface and NDT (100 % visual-measurement, 100 % UT to detect cladding delamination, and 100 % LPI) are performed.

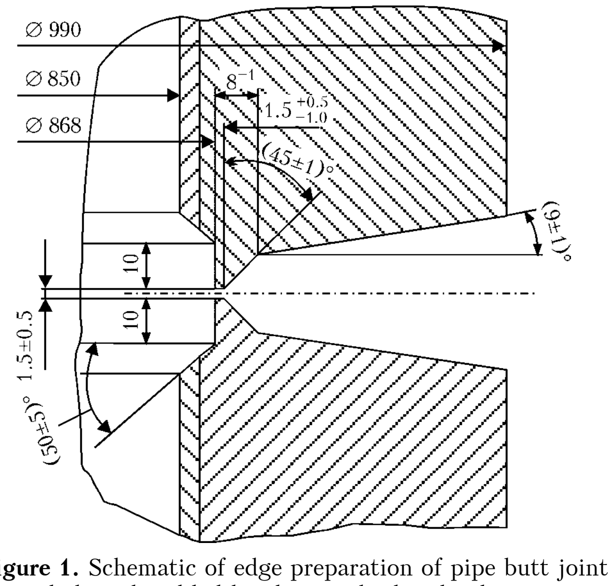

Figure 1. Schematic of edge preparation of pipe butt joint from clad steel welded by the standard technology

However, as a result of an increased radiation background in the zone of steam generator and piping, it became necessary to develop a welding technology, ensuring a lowering of welder exposure and eliminating their working inside the made pipe joint.

The objective of this work was development of the technology of welding from one side from the outside of clad pipelines of the primary coolant circuit of NPPs that allows lowering both the radiation load on personnel, and labour consumption of repair-welding operations.

Welded joints from bimetal steels are a complex system in terms of metallurgy that forms at joining of metal with different alloying and belonging to different structural classes. Proceeding from alloying and structure, distinction can be made between weld sections on the cladding layer level, in the zone of transition from the cladding layer to the weld of the base low-alloyed layer and the base weld. Joint sections of both the base and cladding layers can be included into the category of similar steel joints. Transition sections, where layers with markedly different alloying levels, structure and properties are joined, belong to the category of joints of dissimilar metals (steels). Therefore, when making welded joints from two-layer steel, the regularities of formation of structure and properties should be taken into account, as well as possible problems, characteristic for welding similar low-alloyed or carbon steels, high-alloyed steels and dissimilar steel joints.

In welding of cladding layers from austenitic steels, a possible problem is formation of hot (primarily, solidification) cracks. A high technological strength is achieved by weld metal alloying with molybdenum and manganese at limitation of the concentration of easily liquating impurity elements (sulphur, phosphorus and silicon) in the deposited metal. A highly efficient measure for prevention of solidification crack development in austenitic welds is producing deposited metal with such Cr_{eq}/Ni_{eq} ratio, which ensures primary solidification with formation of δ-ferrite. A criterion for realization of the mechanism of primary solidification with δ-ferrite formation is controlling its residual fraction in the weld metal at room temperature. However, excessive growth of the fraction of ferrite at increase of ferritizer concentration relative to austenizers, may lead to a reverse effect — crack resistance lowering. In [1] it is shown that for Cr–Ni welds with 20–22 % Cr lowering of solidification crack resistance is observed at δ-ferrite content of more than 40–50 %. 2–8 % of δ-ferrite is optimum in terms of ensuring a high resistance to solidification cracking. To prevent formation of chromium carbides at sensitizing heating and development of intercrystalline corrosion in operation, the deposited metal is further alloyed by active carbidizers. The above principles of deposited metal alloying are applied in practice when making a corrosion-resistant facing layer on the inner surface of clad pipes and nuclear reactor case. For this purpose, welding consumables of alloying systems of 25 % Cr–13 % Ni type are used to make the first layer of cladding over low-alloyed steel, and those with stabilization by niobium of 20 % Cr–10 % Ni–2 % Mn–Nb type are used for the second layer.

Transition sections between the high-alloyed and low-alloyed metal can be a special problem in clad steel welding. Depending on welding consumable alloying and degree of its mixing in the weld metal with the melt of high-alloyed and low-alloyed metals (that depends on the welding mode), a martensite-containing structure can form [2, 3]. Such welds can demonstrate brittle fracture susceptibility. Possibility of solidification or cold cracking is not ruled out, either. In addition, at differences in the alloying system and structural class of the base and consumable materials brittle interlayers can form at the weld pool walls in the section of incomplete mixing [3, 4]. Such interlayers form, for instance, in welding of carbon or low-alloyed steel using high-alloyed welding consumables.

Diffusion redistribution of carbon also affects formation of structural inhomogeneity in the transition sections of joints from steels of various structural classes. This phenomenon is visible on the boundary between the low-alloyed or carbon base metal and weld with a higher content of alloying elements and active carbidizers [3–5]. Carbon diffusion towards the more alloyed weld metal results in base metal forming a zone depleted in carbon and having a lower hardness, and the weld developing an interlayer with a high carbon concentration and high hardness (here carbon accumulation promotes an increase of hardness of martensite interlayer, forming as a result of inhomogeneous mixing of the deposited and base metal). Thus, it is experimentally established that in the transition section between steel 20–austenitic weld, hardness in the martensite interlayer in the zone with higher carbon concentration was *HV* 500–650, in steel 20 in the depletion zone adjacent to the weld it was *HV* 180–200, and at a distance from the weld it was *HV* 200–250. Carbon redistribution can occur in welding and at postweld heat treatment. It is supposed that this process also affects the stress-strain state of the metal [4]. Phase inhomogeneity in the fusion zone results, first, in the risk of brittle fracture development in the low-ductility metal, secondly, the zone of base metal with a variable carbon content can be subjected to a special kind of stress corrosion fracture in service [5]. As an illustration of nonuniform redistribution of carbon between pearlitic steel and high-alloyed steel, Figure 2 shows the microstructure of the transition section of bimetal between the cladding and load-carrying layers. In the Figure a region with carbon accumulation in the austenitic layer has a dark colouring. In the adjacent low-alloyed metal in the carbon depletion zone a coarse-grained purely ferritic structure, having a low hardness, formed.

Prevention of martensite formation in the structure of intermediate welds (similar to welding of austenitic and low-alloyed steels) is

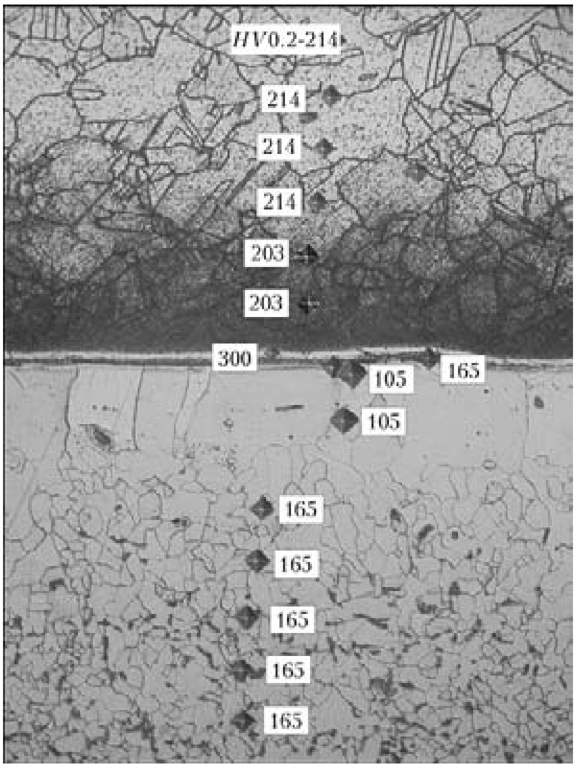

Figure 2. Microstructure (×100) of bimetal in the section of transition from boiler pearlitic steel (*below*) to austenitic cladding layer (*above*)

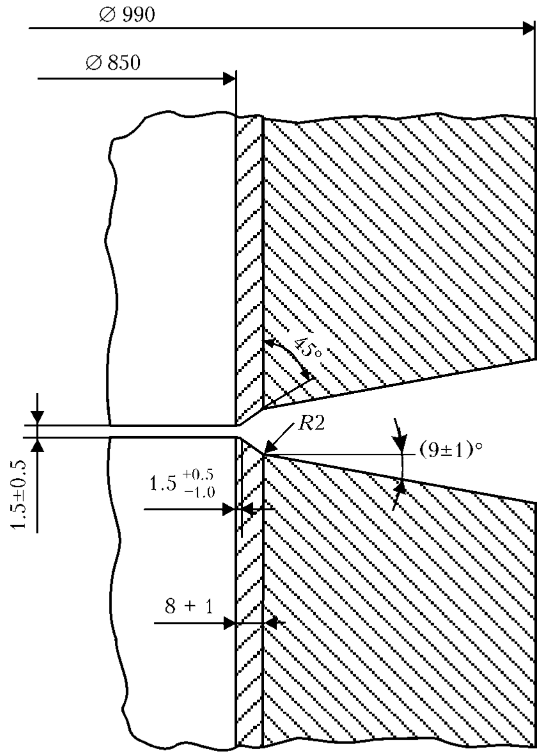

Figure 3. Schematic of edge preparation for welding from one side of pipe joint from clad low-alloyed steel

achieved through application of welding consumables with «higher austeniticity», providing the resultant, purely austenitic or austenitic-ferritic primary crystallization. Reducing the width of variable composition zone at the weld pool walls and martensitic interlayers in them requires ensuring an increased gradient of concentrations of austenizers in this zone. The latter is also achieved by application of welding consumables with increased nickel content. These measures, however, based on application of welding consumables of Cr–Ni or Cr–Ni–Mo systems do not eliminate diffusion displacement of carbon from low-alloyed metal into the high-alloyed weld. This problem can be solved by application of Ni-based welding consumables or facing the low-carbon steel edge by metal with low carbon content.

Welding of the base layer from low-carbon quenching steel of the bainitic class involves the need to prevent delayed fracture. This requires application of preliminary and concurrent preheating. To eliminate stresses and ensure the required mechanical properties of weld metal, welded joints are subjected to high-temperature tempering after welding.

Considered special features of making clad steel welded joints were taken into account in this work.

Selected configuration of the groove for welding from one side (Figure 3) ensures the possibility of sound performance of the root weld in the cladding layer zone. When making the joints both manual welding processes (coated electrode arc welding or nonconsumable electrode argon-arc welding), and automatic argon-arc welding can be applied using the currently available welding equipment.

For welding the root pass and filling the groove in the cladding layer filler wire of 04Kh20N9G2B type should be used, which is envisaged by the rules and norms in nuclear power engineering (PNAE G-7-01–89) for argon-arc welding of corrosion-resistant Cr–Ni steels. The above wire ensures the required corrosion resistance of the weld metal and its high hot cracking resistance due to formation of δ-ferrite. For coated electrode manual arc welding electrodes ensuring similar alloying of the deposited metal, namely TsT-15K, EA-898/21B should be applied.

Groove filling in the base layer can be performed using welding consumables envisaged in PNAE G-7-01–89 for welding 10GN2MFA steel: manual arc welding with coated electrodes PT-30, argon-arc welding with Sv-10GNMA filler wire. For argon-arc welding Sv-08G1NMA wire was also certified and allowed for application [6]. Under the repair conditions it is rational to use the automated welding process, eliminating long-term staying of welders at the pipe joint. Therefore, automatic nonconsumable electrode argon-arc welding using Sv-08G1NMA wire was selected in this study. Checking the groove filling with the above wire, starting with austenitic metal of the cladding without making an intermediate weld with special alloying showed that metal with a martensitic structure with high hardness (approximately *HV* 450) forms in the first passes of such a weld. At the same time, hardness of weld metal of 08G1NMA type and 10GN2MFA steel after the thermal cycle of welding is on the level of *HV* 260–270 and *HV* 280–303, respectively.

To avoid the risk of embrittlement of sections of low-alloyed weld metal of 08G1NMA type deposited on the austenitic underlayer of 18-10 type, the technology of welding with a transition layer was optimized. Transition layers were made using Ni-based (Ni–20Cr, Ni–3Ti) welding wires, low-carbon wire of Armco-iron type and austenitic Cr–Ni–Mo wire Sv-10Kh16N25AM6, traditionally applied for welding dissimilar steels.

It should be noted that the advantage of Ni-based consumables is, first of all, prevention of brittle structure formation in the weld metal, also at the fusion zones, secondly, formation of lower stresses in the joint zone in connection with values of linear expansion coefficient close to those of steels with δ-lattice. In austenitic Cr–Ni steels this coefficient is approximately 1.5 times higher than that of ferritic ones. Application of Sv-10Kh16N25AM6 wire allows lowering the risk of martensite formation in welds, because of an increased content of nickel. It, however, does not prevent formation of diffusion carbon interlayers between the low-alloyed steel and intermediate weld, because of its high content of active carbidizers, namely chromium and molybdenum.

The Table gives the results of measurement of distribution of hardness values in the sections of cladding austenitic layer–intermediate layer–load-carrying weld. Tempering of test samples (650 °C, 2 h) was conducted at the temperature recommended for welded joints of 10GN2MFA steel. Results show that mixing of load-carrying weld metal with the intermediate layer of 10Kh16N25AM6 type leads to formation of a harder and, accordingly, more brittle intermediate structure. The used tempering temperature practically does not influence the hardness in the zone of transition to weld metal of 08G1NMA type. At the same time, a certain increase of hardness in the austenitic metal is in place, that is, probably, due to development of dispersion hardening at precipitation of carbide (in the case of Cr–Ni steel of 18-10 type), and intermetallic phases (in the region of Ni–3Ti alloy).

Hardness values *HV*50 in the zones of weld metal with different alloying of intermediate layers

Joint section, material	After welding	After tempering
Cladding – 18Cr–10Ni	200	225
Intermediate weld – Ni–20Cr	214	200–215
Weld – 08G1NMA	175–232	160–180
Cladding – 18Cr–10Ni	185–200	223–250
Intermediate weld – Ni–3Ti	152–161	150–200
Weld – 08G1NMA	286–293	300
Cladding – 18Cr–10Ni	200	216
Intermediate weld – Armco-iron	237–396	230–300
Weld – 08G1NMA	254–262	250–260
Cladding – 18Cr–10Ni	190–200	206
Intermediate weld – 10Kh16N25AM6	210	175–206
Weld – 08G1NMA	330–450	300–400

More uniform, proceeding from hardness values, are joint sections with an intermediate layer from nickel alloys, as well as with a layer of Armco-iron. In the layer of Armco-iron-base weld metal, hardness is somewhat higher; these values, however, are on the level of hardness characteristic for welds of 08G1NMA type.

Welding of technological samples showed that hot microcracks are found in the sections of transition from the nickel intermediate layer to the weld, made with low-alloyed wire 08G1NMA. They form in the metal, produced at mixing of the nickel layer with low-alloyed deposited metal and can partially propagate into the lower-lying high-nickel layer. Weld in these sections has a columnar structure characteristic for the cast metal. Sites of crack initiation and propagation are intercrystalline zones, which are characterized by accumulation of liquated impurity elements, as well as boundaries of austenitic grains containing chains of discrete phases, which coincide with intercrystalline regions (Figure 4).

Proceeding from the conducted experiments welding wire from Armco-iron was selected for performance of the intermediate layer.

Further filling of the groove in the base layer was performed by manual arc welding with PT-30 electrodes. Used preheating and concurrent heating was 170–200 °C. Welding was followed by high-temperature tempering at the temperature of 650 °C. Weld metal had a bainitic structure with isolated microregions of ferrite. The joint has no defects (Figure 5). Mechanical properties of base weld metal correspond to the level of properties characteristic for 10GN2MFA steel joints ($\sigma_t \approx 640$ MPa, $\sigma_{0.2} \approx 550$ MPa, $\delta \approx 17.6$ %,

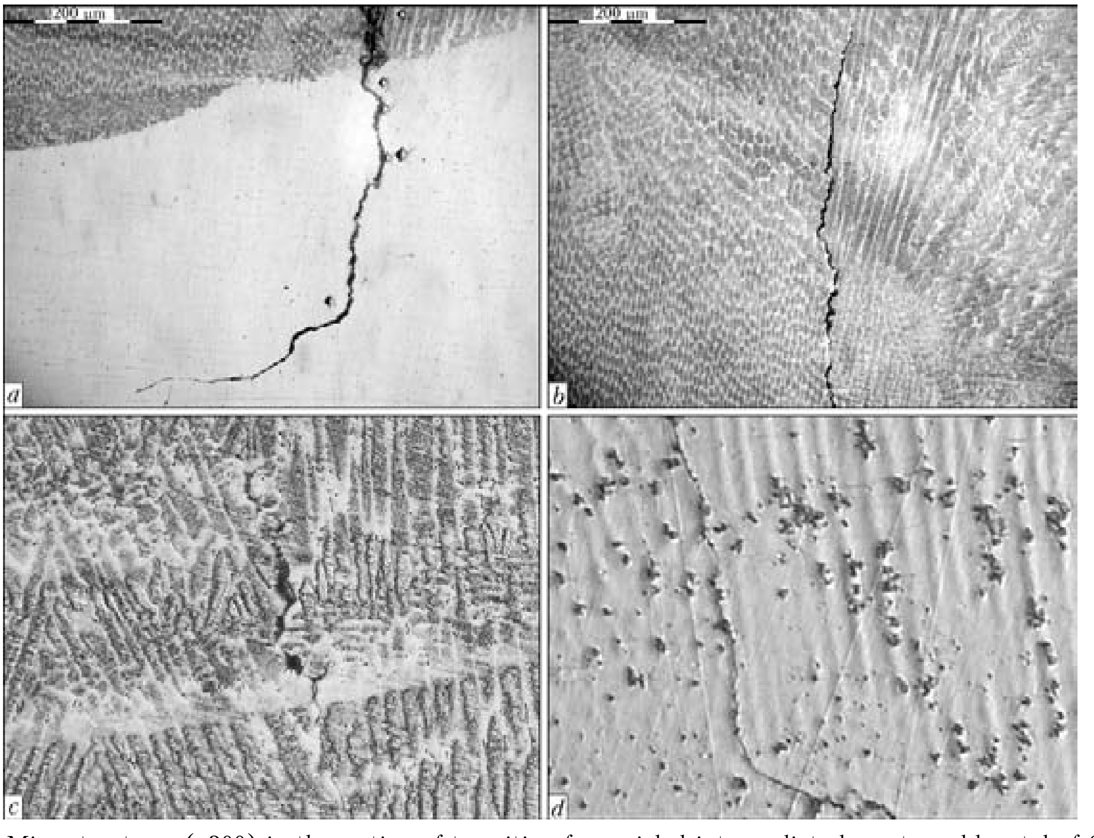

Figure 4. Microstructures (×200) in the section of transition from nickel intermediate layer to weld metal of 08G1NM type: *a*, *b* — cracks in the fusion zone of Ni–3Ti sublayer and load-carrying weld (*a* — in nickel metal, *b* — in the section of fusion of nickel layer and load-carrying weld metal); *c* — microcrack in the section of fusion of Ni–20Cr type layer with the load-carrying weld; *d* — secondary boundary, coinciding with intercrystalline zone, with precipitations of dispersed phases in the transition layer of Ni–20Cr type (potential path of crack formation)

$\psi \approx 69$ %, $KCV \approx 160–200$ J/cm^2). At application of automatic argon-arc welding with Sv-08G1NMA filler wire the following properties of weld metal are provided [6]: $\sigma_t \approx 690$ MPa, $\sigma_{0.2} \approx$ ≈ 600 MPa, $\delta \approx 24.2$ %, $\psi \approx 73$ %, $KCV \approx$ ≈ 270 J/cm^2.

Welding from one side is also used in welding of joints of clad pipes of up to 500 mm diameter from heat-resistant steels. In this case welding up the entire section of the joint is conducted with austenitic welding electrodes, used for welding dissimilar steels (EA-395/9). However, such joints have an increased level of residual welding stresses due to shrinkage of the austenitic weld, and also formation of brittle interlayers in the fusion zone and partial softening of the adjacent layers of base metal due to hydrogen diffusion into the weld are observed. As was noted, non-uniform structure and high stresses in the HAZ metal adversely affect performance of joints welded with austenitic consumables. It is rational to apply instead of such a technology, the above-described process of welding with a transition layer between the austenitic root weld and pearlitic filling weld. Welding (for instance, for pipes from 10GN2MFA steel) should be performed in

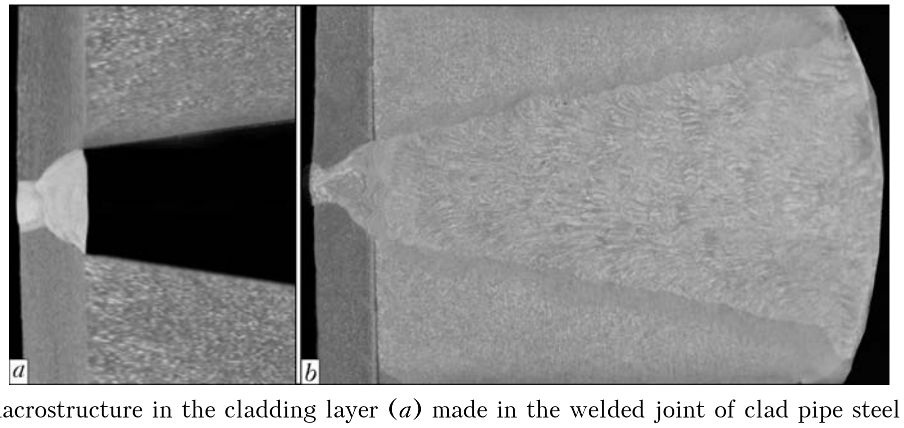

Figure 5. Weld macrostructure in the cladding layer (*a*) made in the welded joint of clad pipe steel by the developed technology (*b*)

the following sequence: welding up the root pass and groove root in the area of the cladding layer — by austenitic material of 04Kh20N9G2B type; making the transition weld from low-carbon ferrite metal (Armco-iron); filling the groove with electrode material, designed for welding the base weld (Sv-08G1NMA, Sv-10GNMA in argon-arc welding, PT-30 electrodes in manual arc welding) with compulsory preheating and concurrent heating; performance of local high-temperature tempering of the joint. Such an approach ensures a uniform structure and low level of residual (after tempering) stresses in the zone of welded joint of the base low-alloyed layer that should improve the service reliability of the joint as a whole.

Thus, the result of the performed work is confirmation of basic possibility of performance of welding from one side of pipe butt joints of clad 10GN2MFA steel. A feature of the proposed development is making the transition weld with low-carbon ferritic metal to eliminate formation of brittle interlayers. Application of the developed technology allows considerably lowering the labour cost, and improving the sanitary-hygienic working conditions of personnel. The proposed approach also allows replacing the traditional technology of welding the clad pipes using austenitic weld metal by making a ferritic weld that enables improvement of welded joint strength.

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CHROMIUM-MANGANESE CONSUMABLES FOR WELDING OF HIGHER-STRENGTH STEELS WITHOUT PREHEATING AND HEAT TREATMENT

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Data on new chromium-manganese electrodes of grades ANVM-2, ANVM-3 and flux-cored wire PP-ANVM-3, designed for welding and surfacing of higher strength steels, are given. The paper presents the results of the evaluation of the structure and mechanical properties of welded joint metal made with new welding consumables, as well as areas of their application.

Keywords: *arc welding, chromium-manganese electrodes, flux-cored wire, alloyed carbon steel, austenitic weld metal, fusion zone, mechanical properties, area of application*

Current mining, metallurgical and other branches of machine building provide for a manufacture of different parts and assemblies from alloyed steels 40Kh, 30KhGSA and others of high strength σ_t = 600–800 MPa and higher. The necessity of application of preheating and post-weld tempering is caused by the cold cracks that can be formed in welding of such hardenable steel. This complicates a technological process and can be impossible during manufacture of massive large dimension parts.

High-alloy nickel welding consumables Sv-08Kh20N25G8M6, Sv-08Kh20N9G7T and others providing formation of austenite weld metal structure are as a rule used for welding of the hardenable steels in order to avoid performance of labor-consuming thermal operations. Low strength of the austenitic weld metal provides a necessity of its performance with high reinforcement in order to increase strength of the welded joint. Labor-intensiveness of welding and consumption of expensive welding consumables dramatically increase due to this. At that rising of concentration of stresses in the places of transfer from thickened weld to base metal results in reduction of working capacity of the welded joint.

Application of Cr–Mn alloying system (σ_t = = 590–690 and 980 MPa) at 0.2 and 0.4 wt.% C