# OPTIMISATION OF CHEMICAL COMPOSITION AND STRUCTURE OF METAL OF REPAIR WELDS DURING ELIMINATION OF DEFECTS IN PIPE WELDED JOINTS USING MULTILAYER WELDING

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The structure and properties of metal of repair welds, produced using multipass welding during elimination of defects in welds of gas and oil pipelines, were investigated. The changes of chemical composition and impact toughness at negative temperatures and also peculiarities of structure characteristics of metal of separate passes of repair welds were determined. It was shown that in manual arc and mechanized submerged arc welding and welding in shielding gases applying consumables, conventional for manufacture of pipes, the metal of the last passes of repair weld is excessively enriched by different alloying elements (manganese, silicon, chromium, molybdenum, etc.) present in such materials. This leads to the formation of unfavorable structure: areas of upper bainite, developed grid of polygonization boundaries, boundary precipitates of carbon second phase, which in its turn provokes formation of cold cracks in welds. Considering the results of investigations the requirements were developed to the chemical composition of welding wire for repair of defects in pipe welds using multipass welding, providing restriction in the content of alloying elements. In multipass submerged arc welding it was also offered to use aluminate flux. The wire of recommended composition was tested during repair of defects in pipe welds using welding in shielding gas and provided high impact toughness of metal of repair welds in combination with a sufficient resistance against cracks formation. The results of investigations can be used for repair of defects in welds during manufacture of pipes and also in multipass welding of other metal structures. 5 Ref., 4 Tables, 7 Figures.

***Keywords:*** *pipe, weld, repair, defects, multipass welding, welding consumables, impact toughness, structure, cracks*

It is known that during manufacture of large-diameter pipes, welded using multipass submerged arc welding, the elimination of separate inner defects in welds (pores, slag inclusions, lacks of penetrations or lacks of fusion) by their preliminary removal and further filling of formed groove by multilayer welding is admitted in a restricted amount (for example, not more than for 5 % of pipes) [1–3, etc.]. In accordance with the valid standard documents the length of such «repair» area should be restricted by 50–500 mm. It is assumed that qualitative characteristics of such areas, including the level of mechanical properties of metal, should meet the requirements specified to the main welded joints of pipes.

The repair of defects in pipe welds is performed by manual arc welding, mechanized submerged arc welding or welding in shielding gases. The number of necessary passes of repair weld is determined by depth of a groove, formed during removal of defect, which in its turn depends on the site of its location in weld section and thickness of a pipe wall. In typical cases, for example, up to six-ten passes of repair weld are performed for pipes with the wall thickness of 15–20 mm. In CIS countries in mechanized submerged arc welding the fused manganese high-silicon flux AN-60 and wire of the Sv-10G2 type are mainly applied. Such combination of welding consumables provides comparatively low values of tough characteristics of metal of repair weld (at the level of 30 kJ/cm$^2$ at 0 °C).

At the same time the requirements to tough properties of weld metal of pipes themselves, including the sites of defects repair, grew sufficiently. According to the valid standard documents the mean values of impact toughness of metal of welded joints of pipes for main pipelines should be more often of not less than 49 J/cm$^2$ at −20 °C and for the pipelines being laid down under water the same requirements are valid at −30 and even −40 °C.

To provide these values it is necessary to optimize the chemical composition of metal of repair welds including that of welding consumables providing higher alloying.

As is shown in the work [4], during repair of defects in welds of pipes using multilayer welding there is one more problem connected with cold cracks formation in repair areas of welds. It is noted that their formation is predetermined by increase of mass fraction of alloying elements in the last layers of repair welds. Thus, in case of using flux AN-60 and wire Sv-10G2 during repair of defects in longitudinal weld of a pipe with the wall thickness of 15.7 mm the content of manganese in the latter (in our case in the fifth one) pass of repair weld was growing up to 2.4 %, and silicon — up to 1.0 %. To compare, let us note that in the metal of longitudinal weld of pipe, the amount of these elements did not exceed 1.73 and 0.45 %, respectively. As a result, in the metal of closing passes of repair weld the areas with unfavorable structure were formed, which during cooling of metal under the conditions of relatively rigid contour provoked formation of mentioned cold cracks. It should be assumed that in case of application of welding consumables providing higher alloying and larger thickness of a wall of welded pipes, and as a consequence, a small number of passes, the danger of deterioration of metal structure and initiation of cracks in the repair areas will grow.

At the present article the results of investigations, carried out by the authors during solution of task of optimization of chemical composition and structure of weld metal in the sites of defects repair using arc welding, were considered to provide the increased requirements to tough characteristics of weld metal and prevention of cold cracks formation.

The repair (simulation of repair operation of defects located at the depth of about 10–12 mm) was carried out on the specimens of steel X70 1420 × 18.7 mm pipes with longitudinal welds produced under flux AN-60 using wire Sv-08G1NMA. On the specimens, cut out of pipes at the centre of longitudinal weld using specialized electrodes ANR-2, the groove of 15 mm depth was made, which simulated the defect removal. In some cases during use of specimens of pipes with wall thickness of 15.7 mm the depth of groove before welding was 10 mm. The content of main elements in metal of longitudinal weld was in the following ranges, wt.%: 0.05–0.06 C; 1.62–1.79 Mn; 0.429–0.470 Si; 0.008–0.009 Nb; 0.15–0.19 Mo; 0.180–0.236 Ni; 0.015–0.018 Ti. Some variations of separate elements in metal of longitudinal weld are connected with application of steel X70 pipes of different thickness (different chemical composition) in the experiments.

The grooves were filled mainly using mechanized $CO_2$ welding, mixture Ar + 20 % $CO_2$ and under flux, and on the separate specimens — using manual arc welding. The grooves of 15 mm depth were welded up in eight passes, and that of 10 mm depth — in five passes. The typical welding consumables were applied used in manufacture of pipes: for submerged arc welding — wire Sv-08GA, Sv-10G2, Sv-08KhM, Sv-08GM,

**Table 1.** Content of main alloying elements in welding wire, wt.%

| Wire grade | C | Mn | Si | Ni | Mo | Cr |
|---|---|---|---|---|---|---|
| Sv-08GA | 0.09 | 0.95 | 0.05 | 0.14 | – | – |
| Sv-10G2 | 0.10 | 1.70 | 0.05 | 0.12 | – | – |
| Sv-08G2S | 0.09 | 2.01 | 0.85 | 0.11 | – | – |
| Sv-08KhM | 0.08 | 0.50 | 0.20 | 0.14 | 0.50 | 1.02 |
| Sv-08GM | 0.08 | 1.19 | 0.35 | 0.11 | 0.59 | – |
| Sv-08G1NMA | 0.09 | 1.20 | 0.31 | 0.49 | 0.52 | – |
| S2Mo | 0.07 | 1.15 | 0.21 | 0.11 | 0.50 | – |
| GMoSi | 0.10 | 1.11 | 0.60 | – | 0.50 | – |

Sv-08G1NMA, S2Mo and flux AN-60, AN-67B, OR 107, OR 132, OK 10.71, OK 10.74; for welding in shielding gas — wire Sv-08G2S, GMoSi; for manual arc welding — electrodes Schwarz 3K. The chemical composition of welding wires is given in Table 1.

The submerged arc welding was performed using wire of 2.5 mm diameter ($I_w$ = 320–350 A, $U_a$ = 28–30 V, $v_w$ = 17–20 m/h), in shielding gas — using wire of 1.2 mm diameter ($I_w$ = 160–180 A, $U_a$ = 26–28 V), and manual arc welding — using electrodes of 3.2 mm diameter ($I_w$ = = 130–150 A, $U_a$ = 25–26 V).

From the produced joints the specimens were selected to determine the chemical composition of weld metal, its impact toughness and metallographic examinations. The analysis of chemical composition of metal of single passes was performed by spectral method using «Spektrovak 1000» device of Baird Company and diffraction spectrometer DFS-36.

The areas of determination of chemical composition, represented in Figure 1, were located in the metal of longitudinal weld being repaired (area 1), in metal of the first pass of repair weld (area 2), in metal of intermediate passes (areas 3 and 4) and in the metal of closing pass of this weld (area 5).

The tests on impact toughness were carried out at the temperature from −10 to −40 °C on the specimens with a sharp notch marked at the centre of deposit according to GOST 6996.

The microstructure of metal was studied applying optical and scanning electron microscopy at the magnification of 50–500 on the sections after etching in nital (4 % alcohol solution of nitrogen acid), in hot solution of sodium picrate and saturated water solution of picric acid.

It was established that for all the investigated variants of combinations of welding consumables that with increase in number of passes of repair weld, the level of metal alloying was growing naturally. As is seen from Figure 2, the amount of manganese and silicon in metal of the second

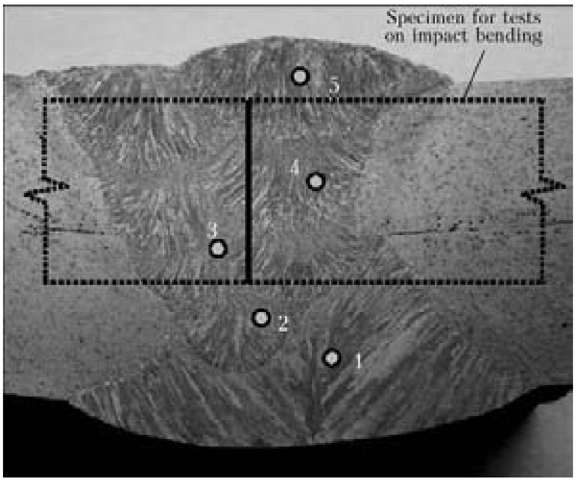


**Figure 1.** Characteristic macrosection of the investigated repair welds and zones of determination of chemical composition 1–5

pass grows to 2.35 and 0.62 %, respectively, and continues growing further in next passes up to the maximal values in the closing pass: 2.85 and 0.99 % respectively. Similarly the content of chromium and molybdenum is changed, which is shown on the example of use of wire Sv-08KhM in the process of defects repairing (Figure 3).

The intensity of growing of mass fraction of any alloying element is determined in the first turn by the applied welding consumables. As is seen from Figure 4, the highest amount of silicon, as was supposed, is present in the last pass of the weld produced using acid high-silicon flux AN-60, moreover, its content in metal of this pass is growing from 0.76 to 0.99 % with increase in mass fraction of manganese in welding wire (to remind, in the longitudinal weld of a pipe the amount of silicon did not exceed 0.45 %). The transition of silicon from flux into the metal of repair weld is considerably decreased with the decrease of $SiO_2$ amount in flux. The minimum growth of amount of silicon is observed during application for the considered purpose of molten neutral flux AN-67B or ceramic aluminate-basic flux of the type OR 132 for the considered purpose.

The content of manganese in the metal of multipass repair welds depends greatly on its amount in welding wire. Thus, using wire Sv-10G2 with 1.7 % Mn the mass fraction of this element in the metal of a last pass amounted to 2.85 %. At a lower amount of manganese, for example, in wire Sv-08G1NMA (1.2 % Mn) or Sv-08KhM (0.5 % Mn), its maximum amount in repair weld was decreased to 1.97 and 1.77 % respectively. The rate of increment of other alloying elements in the investigated multipass welds was also determined by their content in welding wire.

The generalized data of chemical composition of the last passes of repair welds being produced in eight or five passes for different methods of welding and welding consumables are given in Table 2. It is seen that use of almost any of the combinations of welding consumables, usually applied in manufacture of pipes, leads to considerable growth of mass fraction of any alloying elements in the closing passes of investigated welds. Thus, in submerged arc welding the excessive amount of manganese is present in case of using wire Sv-10G2, silicon — flux AN-60, OK 10.71, OK 10.74, chromium — wire Sv-08KhM, molybdenum — wire Sv-08G1NMA, Sv-08GM, Sv-08KhM, S2Mo. The same data were also obtained during application of other welding methods. For example, in the metal of repair

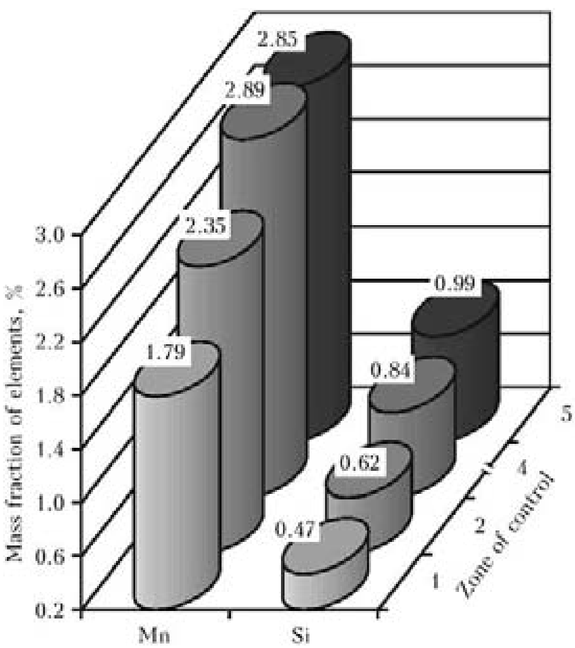


**Figure 2.** Mass fraction of manganese and silicon in metal of different passes of repair weld produced using wire Sv-10G2 and flux AN-60

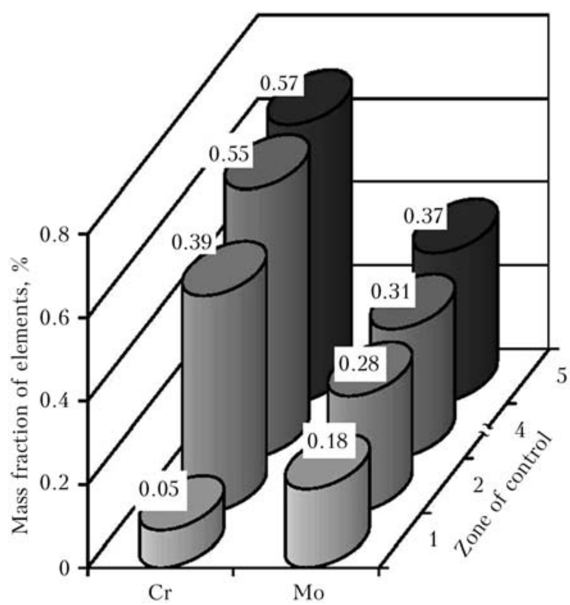


**Figure 3.** Mass fraction of chromium and molybdenum in metal of different passes of repair weld produced using wire Sv-08KhM and flux AN-67B

**Table 2.** Chemical composition of metal of last passes of repair welds (wt.%) produced using different methods of welding and different welding consumables

| Variant number | Welding consumables | | C | Si | Mn | S | P | Cr | Mo |
|---|---|---|---|---|---|---|---|---|---|
| *Manual arc welding* | | | | | | | | | |
| 1 | Schwarz 3K | | 0.055 | 0.268 | 1.22 | 0.011 | 0.015 | 0.05 | 0.422 |
| *Mechanized welding in shielding gas* | | | | | | | | | |
| 2 | Sv-08G2S | $CO_2$ | 0.081 | 0.569 | 1.48 | 0.013 | 0.016 | 0.06 | 0.021 |
| 3 | Sv-08G2S | Ar + 20 % $CO_2$ | 0.089 | 0.810 | 1.40 | 0.014 | 0.016 | 0.06 | 0.022 |
| 4 | GMoSi | Ar + 20 % $CO_2$ | 0.093 | 0.408 | 0.88 | 0.009 | 0.017 | 0.07 | 0.461 |
| *Mechanized submerged arc welding* | | | | | | | | | |
| 5* | Sv-10G2 | AN-60 | 0.073 | 0.990 | 2.854 | 0.016 | 0.021 | 0.05 | 0.003 |
| 6* | | AN-67B | 0.080 | 0.320 | 2.390 | 0.016 | 0.024 | 0.05 | 0.022 |
| 7 | | OR 107 | 0.065 | 0.460 | 2.376 | 0.016 | 0.023 | 0.06 | 0.028 |
| 8 | | OK 10.71 | 0.088 | 0.723 | 2.368 | 0.015 | 0.022 | 0.06 | 0.027 |
| 9 | Sv-08G1NMA | AN-60 | 0.044 | 0.974 | 1.967 | 0.017 | 0.026 | 0.03 | 0.534 |
| 10 | | AN-67B | 0.056 | 0.281 | 2.348 | 0.015 | 0.022 | 0.03 | 0.515 |
| 11 | | OR 107 | 0.059 | 0.442 | 2.117 | 0.017 | 0.023 | 0.04 | 0.404 |
| 12 | | OK 10.71 | 0.071 | 0.670 | 2.156 | 0.015 | 0.024 | 0.05 | 0.431 |
| 13* | Sv-08KhM | AN-60 | 0.072 | 0.761 | 1.770 | 0.017 | 0.025 | 0.67 | 0.368 |
| 14* | | AN-67B | 0.073 | 0.254 | 1.748 | 0.017 | 0.027 | 0.57 | 0.356 |
| 15 | | OR 107 | 0.049 | 0.431 | 1.701 | 0.016 | 0.023 | 0.58 | 0.411 |
| 16* | S2Mo | OK 10.74 | 0.059 | 0.613 | 1.740 | 0.016 | 0.028 | 0.07 | 0.461 |
| 17* | Sv-08GM | OK 10.74 | 0.060 | 0.618 | 1.600 | 0.017 | 0.029 | 0.06 | 0.470 |
| The variant numbers of repair welds produced in eight passes are marked with asterisk. | | | | | | | | | |

welds being welded in shielding gas, the content of silicon increases (wire Sv-08GA, in particular during welding in the mixture Ar + 20 % $CO_2$) or molybdenum (wire GMoSi). In the metal of last passes of repair welds produced using manual arc welding using electrodes Schwarz 3K with the mass content of molybdenum 0.5 % the increased amount of this element was observed.

The increased content of alloying components in metal of repair welds is accompanied, as was noted, by corresponding change of its structure. Thus, in making the multilayer deposits by manganese wire Sv-08GA or Sv-10G2, when the content of manganese in metal of last passes increases up to 2.4–2.8 %, in the structure of metal, except of acicular forms of ferrite, considerable amount of lamellar ferrite with ordered carbide phase, Widmanstatten ferrite and also separate areas of polygonal pre-eutectoid ferrite and pearlite is observed. For metal with such structure very low characteristics of toughness are typical. The enrichment of such metal with silicon from flux or wire results in additional embrittlement of ferrite matrix.

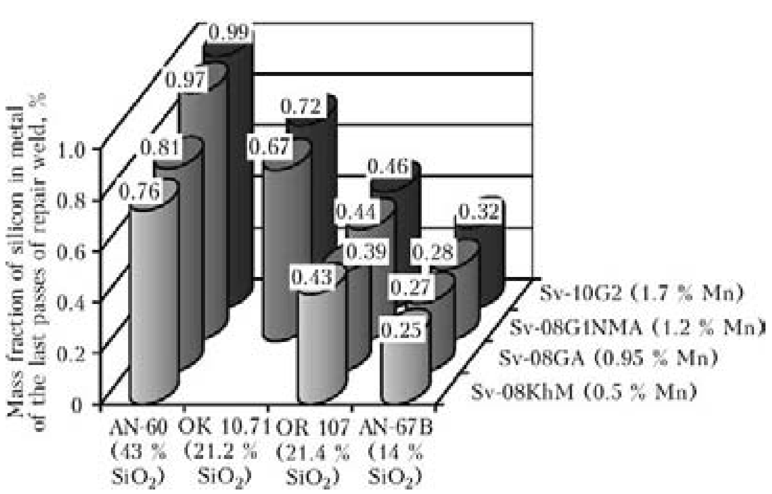


**Figure 4.** Dependence of silicon content in metal of the last passes of repair weld on the applied welding consumables (in brackets the content of manganese in the wire and $SiO_2$ in flux is given)

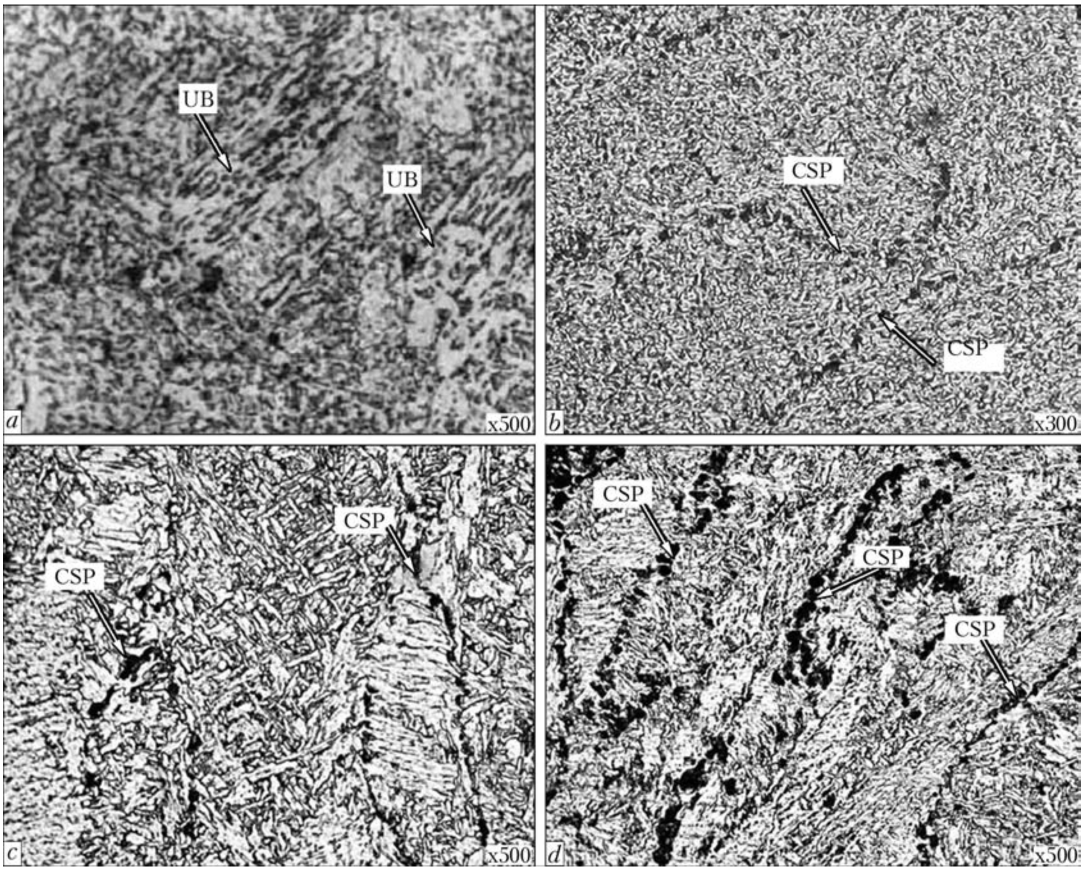


**Figure 5.** Characteristic microstrucutre of metal of the last (*a*) and intermediate (*b*–*d*) passes of repair welds with increased content of alloying elements (etching in 4 % solution of nitrogen acid): *a*, *b* — mechanized submerged arc welding with wire S2Mo, flux OK 10.74 (Table 2, variant 16*); *c* — manual welding, electrodes Schwarz 3K (Table 2, variant 1); *d* — mechanized welding in shielding gas, wire GMoSi, Ar + 20 % $CO_2$ (Table 2, variant 4); UB — areas with the structure of upper bainite; CSP — carbon second phase (carbides, MAC-phase)

When producing multilayer repair welds using alloyed wires (Sv-08G1NMA, Sv-08KhM, Sv-08GM, S2Mo, GMoSi) with mass fraction of molybdenum of more than 0.5 %, due to increased content of manganese, molybdenum and chromium, decreasing the temperature of austenite transformation, alongside with acicular ferrite in the metal of last passes the areas of upper bainite (Figure 5, *a*) are formed, the amount of MAC-phase is increased, the developed grid of polygonization boundaries is formed. The formation of single polygonization boundaries in metal of repaired weld, produced using mentioned wires, begins during welding of the second pass and in the third and the following passes these boundaries are located in the form of closed contours. Besides, in the metal of intermediate passes subjected to repeated heating, where the content of molybdenum is already significant, the boundary formations of the second carbon phase are formed: MAC-phase and carbides (Figure 5, *b*). The similar clusters of carbon phase along the boundaries of crystallites and polygonization boundaries are present also in the metal of intermediate passes during manual arc welding (Figure 5, *c*; Table 2, variant 1) and welding in shielding gas (Figure 5, *d*; Table 2, variant 4) using electrodes or wire alloyed with molybdenum. The mentioned structural peculiarities predetermine the decreased resistance of metal of such repair welds against cracks formation, which is proved by the presence of these defects in the investigated specimens in the form of large cracks escaping to the surface of a weld and net of microcracks, localized mainly along the grain-boundary formations of carbon second phase: MAC-phase and carbides (Figure 6).

It is known that to provide tough characteristics of weld metal on microalloyed steel, including pipe steel, molybdenum (or molybdenum in combination with nickel) is actively used as alloying elements. For example, during manufacture of pipes for longitudinal or spiral welds the wire of the type S2Mo and S3NiMo is applied [5]. The results of our tests on impact bending prove also the efficiency of alloying of metal of multipass repair welds using mentioned elements to enhance its tough properties (Table 3). Thus, the application of wire with molybdenum in welding of repair welds in the mixture Ar + 20 % $CO_2$ (wire GMoSi) and under agglomerated aluminate-basic flux of the type OK 10.74 (wires S2Mo and Sv-08GM), as was already expected, allowed obtaining relatively high *KCV*

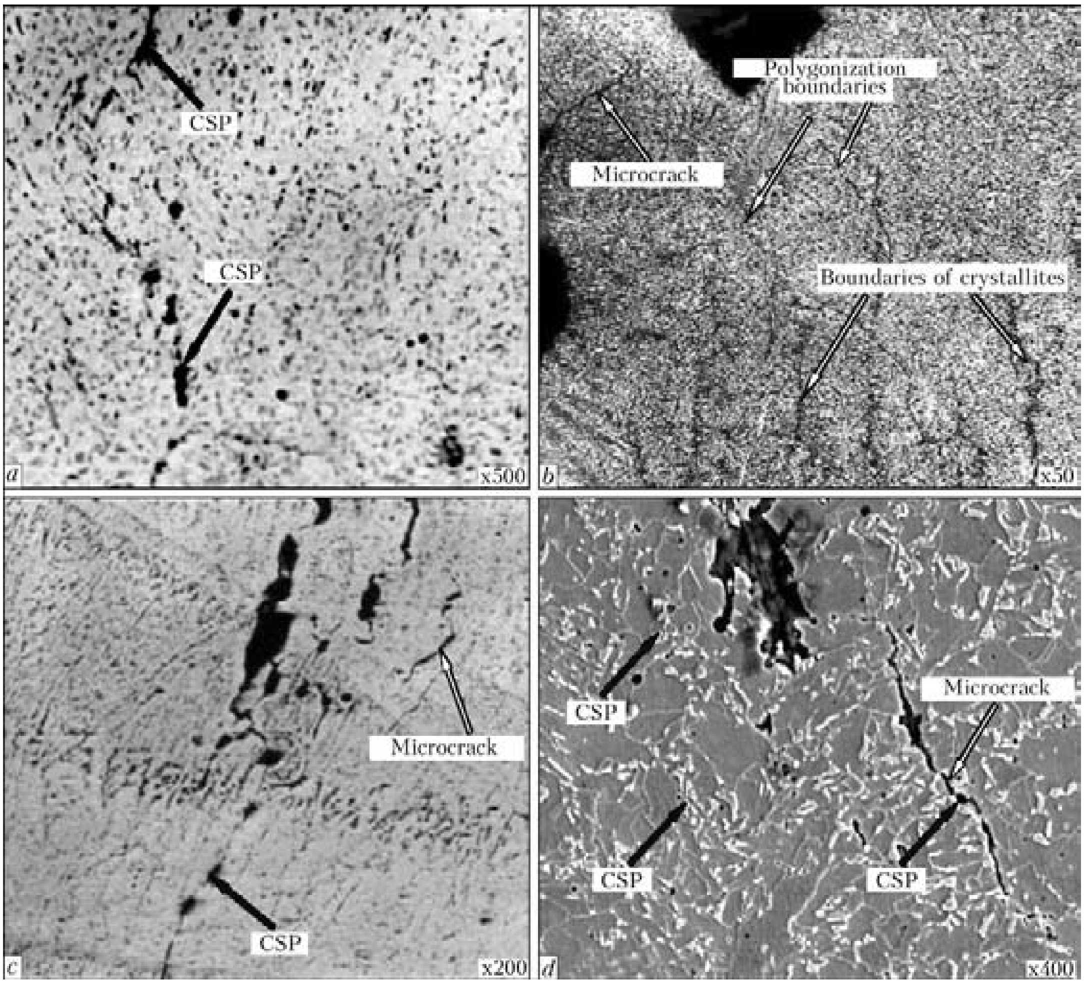


**Figure 6.** Cracks in the metal of repair welds: *a* — etching in the hot solution of sodium picrate; *b*, *c* — etching in the saturated water solution of picric acid; *d* — etching in 4 % spirit solution of nitrogen acid; *a*–*c* — optic; *d* — scanning electron metallography

**Table 3.** Impact toughness of metal of multipass repair weld in use of different welding consumables

| Welding method | Variant number | Welding consumables | $KCV$, J/cm$^2$, at $T$, °C | |
|---|---|---|---|---|
| | | | −20 | −40 |
| Manual arc | 1 | Schwarz 3K | 65.5–107.0 / 81.0 | 40.3–61.2 / 48.8 |
| Mechanized in shielding gas | 2 | Sv-08G2S, $CO_2$ | 27.6–34.3 / 30.8 | – |
| | 3 | Sv-08G2S, Ar + 20 % $CO_2$ | 34.9–48.6 / 42.9 | – |
| | 4 | GMoSi, Ar + 20 % $CO_2$ | 74.5–124.4 / 93.2 | 31.8–63.8 / 53.1 |
| Mechanized submerged arc | 5* | Sv-10G2, AN-60 | 21.2–29.6 / 25.0 | – |
| | 13* | Sv-08KhM, AN-60 | 29.8–35.4 / 32.2 | – |
| | 16* | S2Mo, OK 10.74 | 65.9–75.8 / 70.3 | 37.7–42.4 / 40.8 |
| | 17* | Sv-08GM, OK 10.74 | 77.8–109.8 / 90.7 | – |

*Note*. The variant numbers of welding consumables are given according to Table 2.

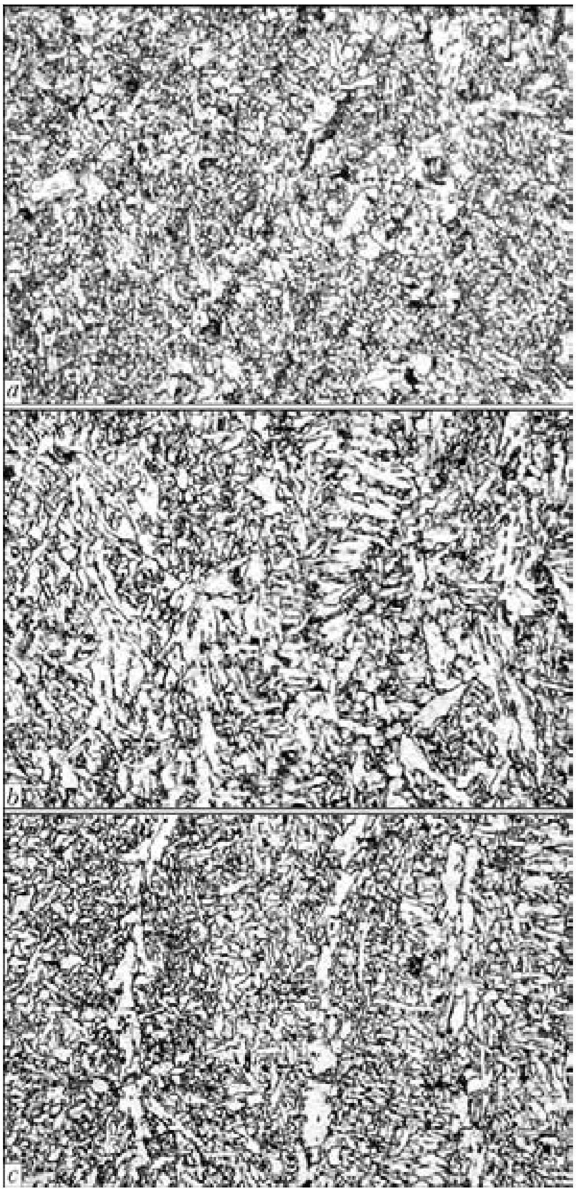

**Figure 7.** Microstructure (×500) of metal of different passes of repair weld produced using mechanized welding in the mixture Ar + 20 % $CO_2$ using wire NiMo1-1G with limited molybdenum content: *a*, *b* — intermediate 2–3 and 5–6 passes, respectively; *c* — last passes

values at the temperature of –20 (on average more than 70 J/cm$^2$) and –40 °C (on average more than 40 J/cm$^2$). However the structure of metal of the last passes of such repair welds, from the point of view of elimination of danger of cold cracks formation, remain unacceptable.

The results of carried out tests allowed formulating the requirements to the chemical composition of welding wire to repair the defects in welds of pipes using multipass welding. Such a wire should contain the limited amount of manganese, silicon and the additional alloying with molybdenum should provide its presence in the metal of the last passes of multilayer repair weld in the amount of not more than 0.3 %. In submerged arc welding the recommended wire should be applied in combination with the flux, for example, aluminate one, excluding the excessive enrichment of metal of multipass weld with manganese and silicon. The wire NiMo1-1G, the chemical composition of which is the following, wt.%: 0.081 C, 1.7 Mn, 0.57 Si, 0.88 Ni, 0.04 V, 0.29 Mo, 0.056 Ti, 0.014 S, 0.017 P, was tested in multipass (a number of passes was eight) welding in the mixture Ar + 20 % $CO_2$ simulating the repair of defect with its preliminary removal in the longitudinal weld of steel X70 pipe of 18.7 mm wall thickness. The applied wire was additionally alloyed with a low amount of nickel. The data of spectral analysis given in Table 4 proved the sufficient stability of chemical composition of repair welds. The content of main alloying elements (manganese, silicon, nickel, molybdenum, titanium) in metal of the first and closing passes practically was not changed, moreover it did not exceed the recommended values.

**Table 4.** Chemical composition of metal of repair welds in welding in the mixture Ar + 20 % $CO_2$ using wire NiMo1-1G, wt.%

| Control zone | C | Mn | Si | Ni | Mo | Ti | V |
|---|---|---|---|---|---|---|---|
| First passes | 0.08 | 1.35 | 0.37 | 0.87 | 0.24 | 0.025 | 0.05 |
| Closing passes | 0.08 | 1.36 | 0.40 | 0.87 | 0.26 | 0.022 | 0.04 |

During the test on impact bending of specimens with a sharp notch the metal of repair welds, produced using the mentioned wire, was characterized by high values of impact toughness at the temperature of –10 (170.4–199.8), –20 (140.9–170.2) and –40 °C (67.8–136.2 J/cm$^2$). At the same time, in the metal of such weld, including its last passes, the sufficiently dispersed structure of acicular ferrite at the absence of polygonization boundaries and areas with coarse grain boundaries formations of phases with the increased carbon content: MAC-phase, carbides (Figure 7), is formed.

The results of investigations can be used also in multilayer welding of other metal structures.


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