Comparative analysis of microhardness distribution showed that in the middle part of the joint produced using foil of Ti–Al system microhardness rises relative to base metal and is equal to about 3000 MPa. On the other hand, in the middle part of the joint made with application of foil of Ag–Cu system microhardness is lower than in the base metal and is equal to 2250 MPa.

Therefore, application of nano-structured foil at RFBW of high-temperature nickel alloy will allow ensuring a uniform highly concentrated heating of the joint zone and lowering the process temperature, thus preventing base metal softening.

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# DEVELOPMENT OF FLUX-CORED WIRE FOR ARC WELDING OF HIGH-STRENGTH STEEL OF BAINITE CLASS

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Given are the results of investigation of the effect of alloying on formation of structure and mechanical properties of the weld metal in gas-shielded flux-cored wire welding, as well as of development of composition of a core of the wire providing the yield strength value of not less than 590 MPa and impact energy of more than 50 J at −50 °C. Optimal additional microalloying with zirconium was determined for the basic C–Si–Mn–Ni–Mo alloying system. This microalloying allows decreasing the volume fraction and size of non-metallic inclusions, as well as increasing the share of dispersed components in metal structure, and provides the required level of strength of the weld metal and its low-temperature tough-ductile properties.

***Keywords:*** *arc welding, low-alloy steel, flux-cored wires, properties of weld metal, structure, non-metallic inclusions, microalloying*

Development of new welding consumables, meeting the high requirements made to mechanical property indices, in particular strength and impact toughness, was necessitated by expansion of production and application of low-alloy steels in building and industry.

The aim of the present paper is development of composition of a wire core providing obtaining of a weld metal with yield strength value of not less than 590 MPa and required values of low-temperature impact energy (more than 50 J at −50 °C) [1]. It is a complex task to achieve such a level of indices using traditional alloying systems.

Experience of development of low-alloy consumables, in particular, flux-cored wires, indicates an appropriateness of application of the alloying systems, close on composition to alloying system of steel to be welded, taking into account different conditions for formation of a metal structure at rolling and welding. As a rule, C–Si–Mn–Ni–Mo(Cr–Cu) system makes an alloying basis. Alloying of the metal in C–Si–Mn–Ni–Mo system due to solid-solution hardening [2, 3] provides necessary indices of strength. Regulation of the tough-ductile properties requires selection of alloying and microalloying system, providing formation of the dispersed structural components which have high resistance to brittle fracture [4, 5].

The investigations were carried out on the pilot batches of flux-cored wire of 1.2 mm diameter with slag-forming system of rutile-fluorite type during downhand welding of AB-1 steel grade plates (400 ×

**Table 1.** Content of alloying elements and additions in the weld metal, wt.%

| Weld number | C | Si | Mn | Ni | Mo | Ti | Al | Zr | S | P |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.07–0.09 | 0.2–0.4 | 1.0–1.4 | 2.0–2.4 | 0.15–0.25 | 0.01–0.015 | 0.025–0.035 | – | 0.011–0.016 | 0.016–0.020 |
| 2 | | | | | | | | 0.007–0.009 | 0.012–0.016 | 0.016–0.020 |
| 3 | | | | | | | | 0.010–0.015 | 0.011–0.016 | 0.016–0.020 |

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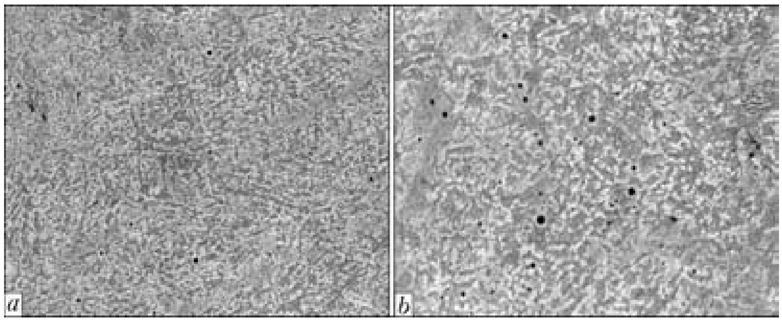

**Figure 1.** Microstructures of the weld metal alloyed by C–Si–Mn–Ni–Mo: *a* — ×1000; *b* — ×2000

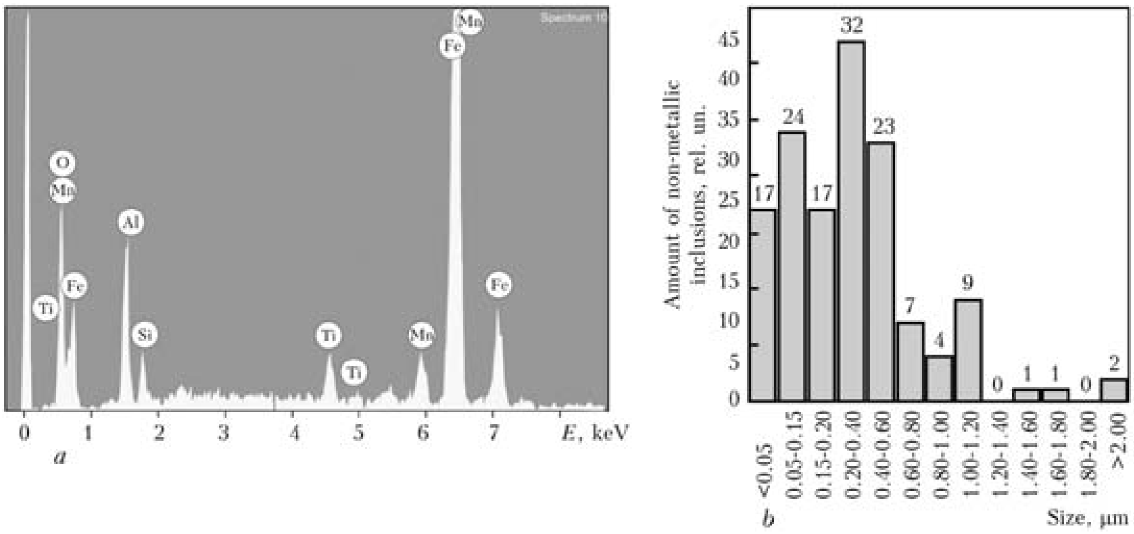


**Figure 2.** Element composition (*a*), and size distribution of non-metallic inclusions in the weld metal of C–Si–Mn–Ni–Mo system (*b*)

× 200 mm size, 20 mm thick with V-groove preparation) in Ar + 15 % $CO_2$ gas shielding atmosphere at heat input 1.3–1.7 kJ/mm (welding current 180–200 A, arc voltage 28 V). A welded joint was cooled up to 90–110 °C before applying of each subsequent bead. Content of the alloying elements and additions in the weld metal varied in the limits, indicated in Table 1. Zirconium microalloying by means of introducing of ferroalloy of Fe–Si–Zr system in the flux-cored wire was applied for obtaining of more high values of weld metal impact energy at low temperatures. Influence of the microalloying was investigated at zirconium content in the weld metal in the limits from 0.007 to 0.015 wt.% (see Table 1). Zirconium

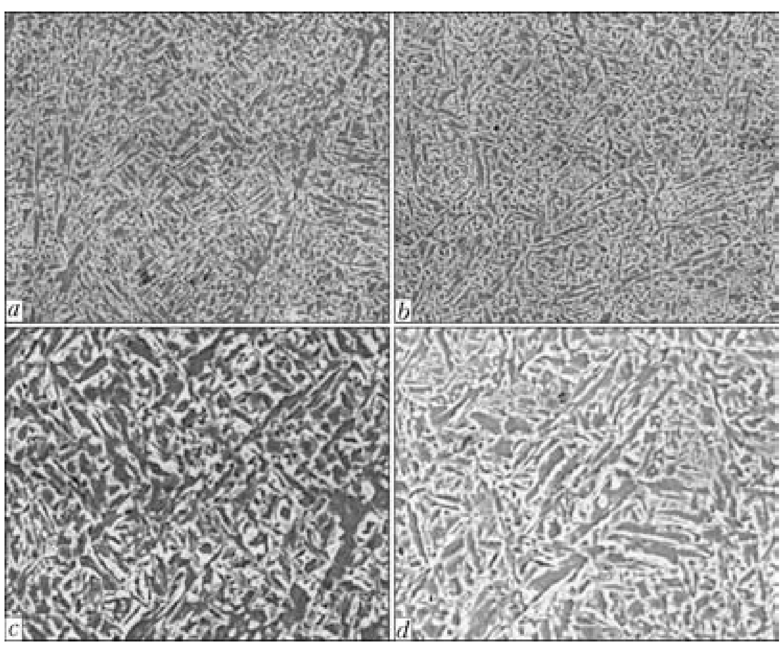

**Figure 3.** Microstructures of the Zr-microalloyed weld metal of C–Si–Mn–Ni–Mo alloying system: *a*, *c* — 0.007; *b*, *d* — 0.015 wt.%; *a*, *b* — ×1000; *c*, *d* — ×2000

acts as a deoxidizer and modifier of the weld metal due to formation of carbides, nitrides and oxides which have an influence on character of structural transformations in steel. The JEOL scanning electron microscope JSM-35CF equipped with energy dispersion analyzer was used for analysis of structure, composition and size distribution of the non-metallic inclusions.

Structure of the weld metal free from zirconium microalloying is a bainite with acicular ferrite areas (Figure 1). Size distribution of the non-metallic inclusions and their compositions are given in Figure 2 (average content of the elements being analyzed in non-metallic inclusions, wt.%: 44.89 O; 0.05 Mg; 14.62 Al; 5.94 Si; 3.58 S; 7.22 Ti; 23.7 Mn). As the analysis of chemical composition have showed, the non-metallic inclusions mainly consist of the oxides of manganese, silicon, aluminum and titanium (Figure 2, *a*). Small amount of oxysulfides, approximately to 3.6 wt.% , is also present in the inclusions.

**Table 2.** Mechanical properties of the weld metal

| Weld number | $\sigma_{0.2}$, MPa | $\sigma_t$, MPa | $\delta$, % | $KV_{-50}$, J |
|---|---|---|---|---|
| 1 | 600–630 | 680–710 | 18–22 | 30–40 |
| 2 | 610–640 | 690–720 | 24–27 | 65–75 |
| 3 | 600–630 | 700–730 | 22–26 | 58–70 |

Values of impact energy $KV_{-50}$, obtained during the tests, make 30–40 J that is lower of the required ones (Table 2).

Fine-dyspersed ferrite of different modifications, i.e. acicular one with disordered second phase and polygonal (proeutectoid) ferrite in a form of fragments of ferrite rings (Figure 3), form the structure of the weld metal after zirconium microalloying. Volume fraction of the dispersed components (bainite) makes around 65 % in the structure of weld metal after zir-

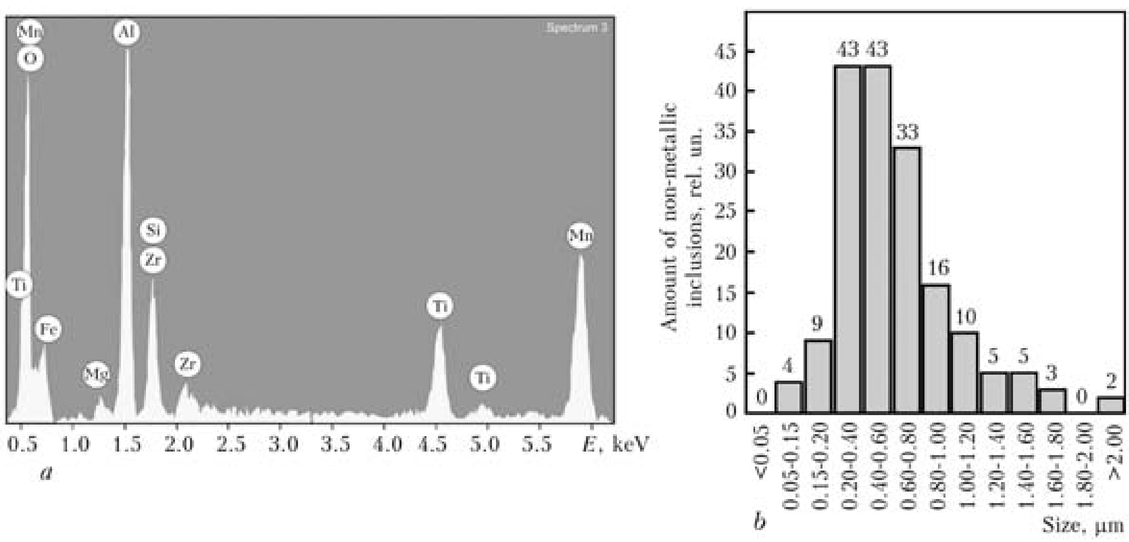


**Figure 4.** Element composition (*a*), and size distribution of non-metallic inclusions in the weld metal of C–Si–Mn–Ni–Mo system after 0.007 wt.% Zr microalloying (*b*)

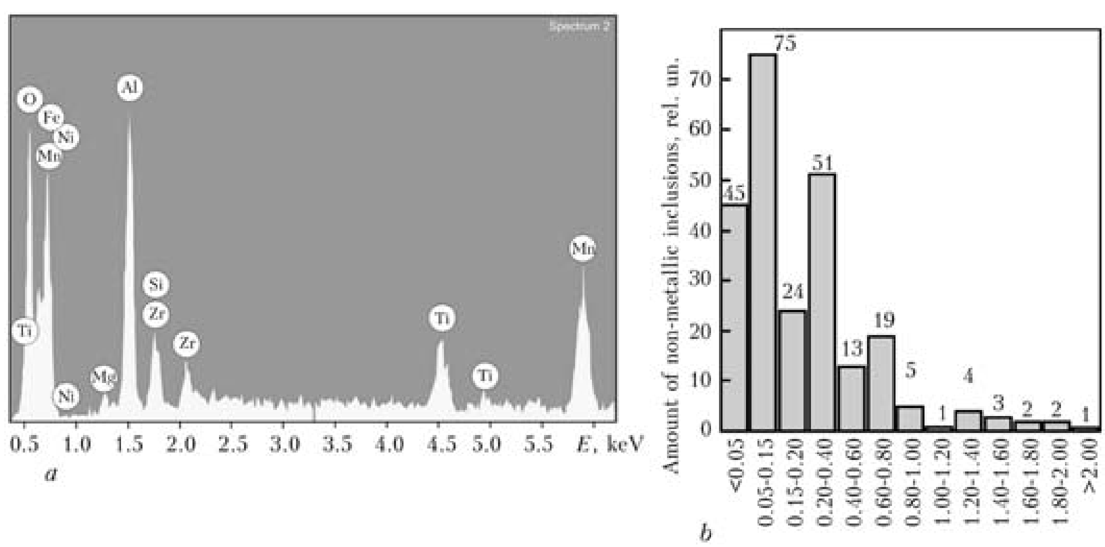


**Figure 5.** Element composition (*a*), and size distribution of non-metallic inclusions in the weld metal of C–Si–Mn–Ni–Mo system after 0.015 wt.% Zr microalloying (*b*)

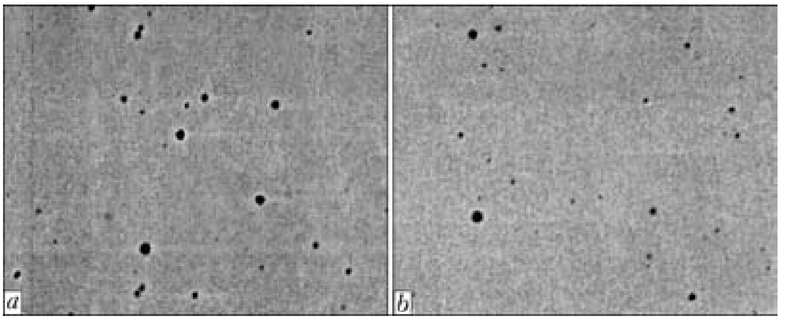


**Figure 6.** Typical distribution of non-metallic inclusions in the weld metal of C–Si–Mn–Ni–Mo alloying system (×3400): *a* — without zirconium microalloying; *b* — with zirconium microalloying on the level around 0.011 wt.%

conium microalloying on a level of 0.007 wt.%, and the rest is polygonal ferrite. Increase of zirconium microalloying up to 0.015 wt.% rises fraction of the dispersed structures up to 70 % and at that dimensions of the needles of the acicular ferrite decrease on average 1.5 times in comparison with the weld metal structure after zirconium microalloying on the level of 0.007 wt.%. Figures 4 and 5 show the compositions of non-metallic inclusions and their size distribution for the welds after zirconium microalloying. Average content of elements being analyzed in the non-metallic inclusions of the weld metal are (wt.%) 46.66 O; 1.45 Mg; 20.17 Al; 4.95 Si; 5.79 Ti; 19.08 Mn; 1.9 Zr after 0.007 wt.% Zr microalloying and 45.64 O; 1.17 Mg; 21.53 Al; 3.14 Si; 6.54 Ti; 16.91 Mn and 5.97 Zr after 0.015 wt.% Zr microalloying.

Volume fraction of the non-metallic inclusions reduces approximately 2 times due to formation of the zirconium oxysulfides which are removed in a slag phase at zirconium microalloying of the weld metal.

Average size of the inclusions itself also reduces approximately by 15 % at that. Zirconium microalloying of the weld metal promotes more uniform distribution of the non-metallic inclusions (Figure 6). Indices of impact energy of the welded joint, according to test results, make 65–75 J at –50 °C, that corresponds to the requirements (see Tables 1 and 2).

The flux-cored wire with the core of rutile-fluorite type was developed as a result of the investigations carried out. It is designed for shielded gas welding of metal structures from steel of not less than 590 MPa yield strength and provides achievement of the necessary level of tough-ductile properties of the weld metal.

## CONCLUSIONS

1. Application of C–Si–Mn–Ni–Mo basic alloying with additional zirconium microalloying allows providing the necessary level of strength (yield strength more than 590 MPa) and impact toughness of the welded joint (impact energy more than 50 J at –50 °C test temperature).

2. 0.007–0.009 wt.% Zr is its optimum content in the weld metal at which reduction of the volume fraction and dimensions of non-metallic inclusions and increase of the fraction of dispersed components in the structure of metal can be achieved.

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