Selection of energy-technological modes of submerged-arc welding with silicomanganese slag for parts of mining equipment

N A Kozyrev, A A Usoltsev, R E Kryukov, A R Mikhno and V Ya Tsellermayer
Siberian State Industrial University, 42 Kirova str., Novokuznetsk, 654007, Russia
E-mail: kozyrev_na@mtsp.sibsiu.ru

Abstract. The paper presents studies of the influence of energy-technological modes of welding on the physical and mechanical properties of welded joints obtained by submerged-arc welding, with the use of slag from silicomanganese production for parts of mining equipment. To study the welding and technological properties, we used a welding flux of 0.45-2.5 mm fraction based on a silicomanganese slag with a chemical composition, wt. %: 0.42 FeO, 16.22 MnO, 29.00 CaO, 41.34 SiO₂, 6.53 Al₂O₃, 1.33 MgO, 0.24 S, 0.022 P, 0.008 ZnO, 0.031 C, 0.31 F, 0.15 TiO₂, 0.025 Cr₂O₃. Automatic welding of 09G2S low-alloy steel under this flux was carried out by Sv-08GA wire. Various welding modes were investigated to ensure the required penetration depth and the absence of external defects (pores, cracks, cavities). Based on the data obtained, the dependences of the influence of the parameters of the welding mode on the mechanical properties of welded samples are plotted. It is shown that changes in the parameters of the current strength, welding speed and voltage can affect the physical and mechanical properties of the weld, as well as the transition of sulfur and hydrogen into the weld.

1. Introduction
At present, welding fluxes made on the basis of manganese oxides such as AN-348A, AN-67, AN-39S are widely used in the Russian Federation [1-3]. At SibSIU a number of works on the use of silicomanganese slag as analogues of such welding fluxes has been carried out [4-10]. In this case, welding modes have a significant effect on the quality indicators of the weld. The purpose of this work is to study the effect of energy-technological modes of submerged-arc welding with the use of silicomanganese slag on the physical and mechanical properties of the welded seam obtained by automatic welding with wire Sv-08GA of low-alloy steel 09G2S.

To study the welding and technological properties, a welding flux was manufactured based on a slag produced by silicomanganese with a chemical composition, wt. %: 0.42 FeO, 16.22 MnO, 29.00 CaO, 41.34 SiO₂, 6.53 Al₂O₃, 1.33 MgO, 0.24 S, 0.022 P, 0.008 ZnO, 0.031 C, 0.31 F, 0.15 TiO₂, 0.025 Cr₂O₃. Previous studies [11] showed that for these fluxes, the most acceptable is the use of fraction 0.45-2.5mm. The research used the equipment of the Scientific and Production Center “Welding Processes and Technologies” and the Center for Collective Use “Materials Science” of Siberian State Industrial University.
2. **Research methods**

Samples for studies of macro- and microstructure, hardness, wear resistance were prepared according to the technique including cutting out samples on KKS 315L cut-off machine, grinding on 3D725 surface grinder, polishing on FROMMIA 835 SE polishing machine.

Welding of specimens of steel 09G2S 20 mm thick was carried out by butt welding without cutting edges with Sv-08GA welding wire using ASAW-1250 welding tractor and the manufactured flux. For comparison, the plates were welded with AN-348 submerged arc. The scheme of cutting samples from welded plates is shown in figure 1.

**Figure 1.** Schematic diagram of cutting out test specimens: 1 – macrosections; 2 – microsections; 3 – hardness; 4 – wear resistance; 5 – determination of hydrogen content

The used flux was dried in the thermal electric furnace for 2 hours at a temperature of 300 °C. Before the surfacing process, the metal plates were cleaned with an angle grinder. Preservation agents, dirt, rust and oxide films were removed from the metal surface. After welding, the surface of the weld metal and the slag crust on the side adjacent to the weld were examined by the visual method and the chemical composition was determined. The chemical composition of slag crusts and fluxes was determined by the X-ray fluorescence method on XRF-1800 spectrometer. The chemical composition of the welds was determined by the atomic emission method on DFS-71 spectrometer. Chemical composition of a number of weld metal samples was determined by chemical methods: for carbon content according to GOST 12344-2003, sulfur according to GOST 12345-2001 and phosphorus according to GOST 12347-77.

Metallographic studies of polished microsections were carried out using OLYMPUS GX-51 optical microscope in a bright field in the magnification range from × 100 to × 1000. The microstructure was revealed by etching the samples in the solution of 4% HNO₃ in ethyl alcohol. The grain size was determined in accordance with GOST 5639-82 at × 100 magnification. Investigation of samples of the deposited layer for the presence of nonmetallic inclusions was carried out in accordance with GOST 1778-70. The polished surface was examined at a magnification of × 100 using a LaboMet-1I metallographic microscope. Macrosections with the size of 20 × 55 × 14 mm were made from the cut samples. The hardness of the samples under study was measured by the Brinell method using an ultrasonic hardness tester USIT-3 in accordance with the requirements of GOST 9012-59.

3. **Results and discussion**

Various welding modes were investigated to ensure the required penetration depth and the absence of external defects (pores, cracks, cavities). The welding modes of the samples were selected by the method of planning experiment 3 (3-1), mode 0 was taken as the basis: current I = 700A, voltage U = 28V, welding rate v = 30 cm/min [12-14]. The investigated modes are presented in table 1.
Table 1. Modes of welding samples.

| Experiment No. | Current strength, A | Voltage, V | Welding rate, cm/min | Heat input, J/cm |
|----------------|---------------------|------------|----------------------|-----------------|
| 0              | 700                 | 28         | 30                   | 42000           |
| 1              | 600                 | 28         | 30                   | 36000           |
| 2              | 600                 | 30         | 32                   | 33750           |
| 3              | 600                 | 32         | 30                   | 38400           |
| 4              | 650                 | 28         | 32                   | 34125           |
| 5              | 650                 | 30         | 30                   | 39000           |
| 6              | 650                 | 32         | 28                   | 44571           |
| 7              | 700                 | 28         | 30                   | 45000           |
| 8              | 700                 | 30         | 28                   | 42000           |

The chemical composition of the investigated welded samples and the parameters of hydrogen concentration are given in table 2.

Table 2. Chemical composition of welds.

| Sample No. | C     | Si    | Mn    | Cr    | Ni    | Cu    | Ti    | Mo    | Al    | S     | P     | N, cm³/100g |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------------|
| 0          | 0.11  | 0.41  | 1.16  | 0.05  | 0.31  | 0.15  | 0.002 | 0.10  | 0.009 | 0.014 | 0.014 | 1.1        |
| 1          | 0.07  | 0.48  | 1.24  | 0.05  | 0.43  | 0.16  | 0.001 | 0.14  | 0.012 | 0.013 | 0.016 | 1.2        |
| 2          | 0.08  | 0.54  | 1.38  | 0.06  | 0.28  | 0.17  | 0.003 | 0.08  | 0.018 | 0.014 | 0.014 | 1.1        |
| 3          | 0.08  | 0.51  | 1.31  | 0.06  | 0.32  | 0.15  | 0.001 | 0.10  | 0.014 | 0.014 | 0.013 | 1.4        |
| 4          | 0.08  | 0.49  | 1.20  | 0.05  | 0.45  | 0.17  | 0.002 | 0.16  | 0.013 | 0.011 | 0.015 | 1.1        |
| 5          | 0.07  | 0.50  | 1.26  | 0.05  | 0.43  | 0.17  | 0.003 | 0.14  | 0.002 | 0.012 | 0.018 | 1.1        |
| 6          | 0.07  | 0.49  | 1.25  | 0.05  | 0.40  | 0.16  | 0.002 | 0.13  | orc.  | 0.012 | 0.015 | 1.0        |
| 7          | 0.09  | 0.50  | 1.23  | 0.04  | 0.41  | 0.13  | 0.001 | 0.14  | 0.014 | 0.011 | 0.011 | 1.3        |
| 8          | 0.09  | 0.50  | 1.31  | 0.06  | 0.31  | 0.17  | 0.001 | 0.09  | 0.019 | 0.014 | 0.013 | 1.0        |
| 9          | 0.07  | 0.53  | 1.27  | 0.05  | 0.37  | 0.15  | 0.002 | 0.12  | 0.010 | 0.015 | 0.016 | 0.9        |

The mechanical properties of the samples under study are presented in table 3.

Table 3. Mechanical properties of welded joints.

| Experiment No. | Tensile strength, σv, N/mm² | Conditional yield stress, σt, N/mm² | Relative extension, δ, % | KCV +20°C | KCV -20°C |
|----------------|-----------------------------|-----------------------------------|------------------------|------------|-----------|
| 0              | 576                         | 482                               | 21                     | 68*        | 22.3*     |
|                |                             |                                   |                        | 63-75**    | 20-26**   |
| 1              | 563                         | 470                               | 21                     | 59.6       | 20.3      |
|                |                             |                                   |                        | 49-81      | 15-31     |
| 2              | 582                         | 481                               | 22                     | 64.3       | 20.6      |
|                |                             |                                   |                        | 60-69      | 17-25     |
| 3              | 560                         | 430                               | 21                     | 66.3       | 32        |
|                |                             |                                   |                        | 52-77      | 25-35     |
| 4              | 570                         | 459                               | 21                     | 59.33      | 30        |
|                |                             |                                   |                        | 56-62      | 27-32     |
| 5              | 570                         | 466                               | 22                     | 67.3       | 32        |
|                |                             |                                   |                        | 59-73      | 31-33     |
| 6              | 563                         | 462                               | 21                     | 59.3       | 29.6      |
|                |                             |                                   |                        | 53-65      | 27-34     |
| 7              | 572                         | 456                               | 21                     | 70.6       | 30.6      |
|                |                             |                                   |                        | 63-85      | 27-33     |
| 8              | 570                         | 464                               | 21                     | 58.3       | 29.3      |
Table 1. Comparison of KCV impact toughness for the welds made with different fluxes.

| Flux Type          | Sulfur Content (wt%) | Phosphorus Content (wt%) | KCV @20°C (J/m²) | KCV @-20°C (J/m²) |
|--------------------|----------------------|--------------------------|------------------|-------------------|
| AN-348A flux       | 553                  | 440                      | 22               | 53-67             |
| (Comparison sample)| 543                  | 368                      | 25               | 52-58             |

* - average values; ** - minimum and maximum values.

**Figure 2.** Dependence of KCV impact toughness on the sulfur content in the weld.

**Figure 3.** Dependence of KCV impact toughness on the phosphorus content in the weld.
Figure 4. Dependence of impact toughness KCV on welding current.

Figure 5. Dependence of ultimate resistance and yield strength on welding stress.

Brinell hardness (HB) of the welded samples under study was measured according to the scheme shown in figure 6. The measurement results are shown in table 4.

Figure 6. Scheme for hardness measuring of welded samples.

Table 4. Hardness measurements of welded samples, HB.

| Experiment No. | Base metal, points | Weld seam, points |
|----------------|-------------------|-------------------|
|                | 1     2     3     4     5     6     7     8     9     10    11    12    13    14    15    16    17    18    19 |
| 0              | 176  160  181  168  178  194  169  186  184  179  185  174  191  186  186  192  174  168  178 |
| 1              | 196  200  172  193  194  186  191  205  204  169  161  191  188  147  193  215  230  220  196 |
| 2              | 162  189  179  185  172  206  197  206  214  210  202  188  199  220  246  237  229  237  235 |
| 3              | 192  235  180  196  234  181  208  189  187  172  235  211  270  247  230  238  209  187  214 |
As it can be seen from figures 7-9, the hardness values depend on the welding modes.

**Figure 7.** Dependence of HB hardness on changes in current strength.

**Figure 8.** Dependence of HB hardness on stress change.
4. Conclusion

The paper presents studies of the influence of energy-technological modes of welding on the physical and mechanical properties of welds obtained by submerged-arc welding, made on the basis of silicomanganese production slag for parts of mining and metallurgical equipment. Automatic welding of 09G2S low-alloy steel under this flux was carried out by Sv-08GA wire. Various welding modes were investigated to ensure the required penetration depth and the absence of external defects (pores, cracks, cavities). It is shown that a change in the parameters of the current strength, welding speed and voltage can affect the physicomechanical properties of the weld, as well as the transition of sulfur and hydrogen into the weld.

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