THE RESEARCH ON SURFACE PROPERTIES
OF WELDING SLAGS AND ELECTRODE COATINGS

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ABSTRACT

The article presents data on the study of surface properties of welding slag and electrode coatings by the method of a maximum pressure in the gas bubble.

As a result of the studies undertaken for welding electrodes with different types of coatings of the surface and interfacial tension of the molten welding slag ($\sigma_{sl}$) and electrode coatings ($\sigma_{co}$) were defined. It was determined that the highest surface tension of the molten welding slag makes possible the downward welding, since the slag generated under the influence of surface forces is prevented from running and does not prevent the welding process. The minimum interfacial tension determines unimpeded formation of the weld, in particular, the penetration bead when welding the root layer. For based coated stick electrodes which provide a guaranteed penetration of a root layer and the stable formation of the back penetration bead during downward welding of the root layer, the most promising is to obtain a welding slag with a low content of F and high content of MnO, FeO and Fe$_2$O$_3$ with the partial substitution of K$_2$O for Na$_2$O.

Keywords: electrode, welding, slag, coating, weld, root, penetration bead, surface tension, interfacial tension.

INTRODUCTION

At the present time the capacity of major pipelines for transportation of hydrocarbons from the place of their extraction to the consumption centers is continuously growing around the world. At the same time the pipe diameter and a working pressure in pipelines are increasing. The pipes with diameters up to 1420 mm with wall thickness up to 48 mm are used. The normative ultimate strength of the metal pipe is 490 - 640 MPa, the working pressure in the pipeline reaches 5.4 - 7.2 MPa with a possible increase to 9.8 - 11.8 MPa, which requires the production of a new pipe with higher strength (690 - 790 MPa) [1, 2].

During development of new Northern deposits of oil and gas the working conditions for pipelines become more complicated, in particular for the welded joints. The experience of operating of pipelines shows that the most destructions of field joints is started with a root seam in areas of greatest stress concentration at the lack of penetration, undercuts, sharp inclusions and other defects. Therefore, the guaranteed penetration of the root layer of the seam with the formation of the smooth penetration bead is considered as a decisive factor in ensuring the operational reliability of the pipe joints.

Currently, the manual arc welding is still a basic method of welding of pipelines in fixed position [3]. Its
significant advantage is the simplicity of the process and the ability to work in various climatic conditions with various places along the pipeline with high quality welds. According to experts, the electrodes will be widely used in future; therefore, improving the technology of manual arc welding with the use of electrodes shall retain relevance for a long time.

The increase in the rate and quality of manual arc welding of pipelines for transportation of gas and oil is principally associated with welding of the root seam whose guaranteed penetration becomes possible only during the downward welding. The slag formed during the welding should not flow under the arc and to interrupt the process [4], and when assembled it should not impede the flow of molten metal into the gap between the ends of the welded pipe.

The physical properties of the slag and the molten coating of the electrodes play a key role in ensuring the downward welding (especially the process and the improvement in quality of welds), which provide the necessary welding-technological parameters of the electrodes [5].

The aim of this paper is to study the surface properties of welding slags and electrode coatings and their influence on the formation of the root layer of the seam of fixed junctions of pipelines.

EXPERIMENTAL

To determine the role of slag protection when downward welding the physico-chemical properties of coatings and welding slags of three groups of electrodes (A- B) were investigated.

The conventional based coated stick electrodes, suitable for welding in all spatial positions, except downward welding were included in Group A. This group is divided into two subgroups. In subgroup A’ the electrodes with poor formation of the penetration bead when welding the root layer of the weld butt joint (SSSI-13/55, E-B121, Fox EV50), in subgroup A» - the electrodes providing the formation of a penetration bead (LB52U) were included.

In group B the universal based coated stick electrodes were included, i.e. allowing the upward and downward welding. This group is also divided into two subgroups. In the subgroup B’ are included electrodes which allow downward welding on a vertical plane, but not guaranteeing the formation of the penetration bead when welding the root layer of the weld butt joints (VSFS-50, LB 26V), and in subgroup B» - special electrodes that provide downward welding including the root layer of the seam with the formation of a penetration bead (Philips 27P, LB86VS).

In group B the cellulosic electrodes and the electrodes on the basis of rutile (WCC-4, OZS-4, B-14) are included.

During the study of coatings of electrodes and welding slag we adopted the concept of «primary» and «secondary» slag. By «primary» we mean the slag melt coating of the electrode, and by «secondary» – a welding slag melted during experiments. By doing so, we conceive that the real welding slag in its properties is located between «primary» and «secondary» slags.

The oxide composition of the experimental welding slag is given in Table 1. The surface tension of the molten welding slag (σ_s) and coatings of electrodes (σ_c) were measured by the method of the maximum pressure in a gas bubble. The scheme of installation is represented on Fig. 1.

The melting of the samples and all measurements were carried out in a molybdenum crucible in Tamman resistance furnace. The temperature was controlled by platinum-rhodium thermocouple. For the formation

Fig. 1. The scheme of installation for measuring the surface tension of melts: 1 - capillary, 2 - holder, 3 - micro lift, 4 - inclined manometer, 5 - Tamman furnace, 6 - crucible with the melt, 7 - thermocouple.
of a gas bubble in the melt the molybdenum capillary with an inner diameter of 4 mm, sharpened to “knife” was applied. Argon was applied as the working gas to protect the melt from exposure to air.

The surface tension was calculated with the formula [6]:

\[ \sigma = \frac{P_{\text{max}} r}{2} \]  

(1)

where: \( P_{\text{max}} \) is the maximum pressure, N/m², \( r \) - the internal radius of the capillary, m.

The preliminary inspection of the device was carried out with the use of water and melts of KCl and PbCl₂, the surface tensions of which are well known.

It is known that for molten oxides and fluorides there is a linear dependence of surface tension on temperature. On this basis, the equations of dependencies of the surface tension on the temperature for each “primary” and “secondary” slag were calculated by the least square method \{LSM\}, which has the form:

### Table 1. Oxide composition of the welding slag.

<table>
<thead>
<tr>
<th>The group of electrodes</th>
<th>Brand electrodes</th>
<th>Coating type</th>
<th>C₂O</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>FeO</th>
<th>Fe₂O₃</th>
<th>MnO</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>A'</td>
<td>SSSI-13/55</td>
<td>Main</td>
<td>43,8</td>
<td>22,8</td>
<td>3,0</td>
<td>4,0</td>
<td></td>
<td>4,9</td>
<td>0,7</td>
<td>1,6</td>
<td>0,69</td>
<td>2,13</td>
<td>10,6</td>
</tr>
<tr>
<td></td>
<td>E-B121</td>
<td></td>
<td>38,2</td>
<td>20,9</td>
<td>6,4</td>
<td>9,0</td>
<td>1,1</td>
<td>4,8</td>
<td>0,5</td>
<td>0,9</td>
<td>1,81</td>
<td>1,42</td>
<td>11,2</td>
</tr>
<tr>
<td></td>
<td>Fox EV50</td>
<td></td>
<td>40,5</td>
<td>18,5</td>
<td>6,8</td>
<td>7,2</td>
<td>0,9</td>
<td>4,3</td>
<td>0,8</td>
<td>0,6</td>
<td>1,14</td>
<td>1,64</td>
<td>12,5</td>
</tr>
<tr>
<td>A''</td>
<td>LB52U</td>
<td></td>
<td>41,0</td>
<td>28,7</td>
<td>6,5</td>
<td>5,0</td>
<td>0,2</td>
<td>4,5</td>
<td>0,7</td>
<td>4,4</td>
<td>1,81</td>
<td>1,11</td>
<td>2,8</td>
</tr>
<tr>
<td>B'</td>
<td>VSFS-50</td>
<td></td>
<td>28,6</td>
<td>22,0</td>
<td>8,5</td>
<td>8,0</td>
<td>0,65</td>
<td>7,4</td>
<td>11,0</td>
<td>4,0</td>
<td>0,19</td>
<td>2,40</td>
<td>3,4</td>
</tr>
<tr>
<td></td>
<td>LB 26V</td>
<td></td>
<td>52,5</td>
<td>27,5</td>
<td>1,8</td>
<td>3,4</td>
<td>2,0</td>
<td>4,3</td>
<td>0,9</td>
<td>1,8</td>
<td>0,19</td>
<td>2,06</td>
<td>3,4</td>
</tr>
<tr>
<td>B''</td>
<td>Philips 27P</td>
<td></td>
<td>34,0</td>
<td>21,4</td>
<td>13,0</td>
<td>7,8</td>
<td>1,8</td>
<td>9,3</td>
<td>0,8</td>
<td>1,8</td>
<td>0,24</td>
<td>2,13</td>
<td>1,6</td>
</tr>
<tr>
<td></td>
<td>LB86VS</td>
<td></td>
<td>48,4</td>
<td>26,4</td>
<td>3,3</td>
<td>4,8</td>
<td>1,6</td>
<td>5,4</td>
<td>0,7</td>
<td>1,6</td>
<td>0,12</td>
<td>2,06</td>
<td>3,4</td>
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<tr>
<td>C</td>
<td>WCC-4</td>
<td>Cellulosic</td>
<td>7,2</td>
<td>19,0</td>
<td>34,8</td>
<td>13,5</td>
<td>2,3</td>
<td>11,2</td>
<td>4,6</td>
<td>1,4</td>
<td>1,39</td>
<td>4,02</td>
<td>0,06</td>
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<tr>
<td>OZS-4</td>
<td>Rutile</td>
<td></td>
<td>3,3</td>
<td>18,0</td>
<td>33,0</td>
<td>14,5</td>
<td>4,0</td>
<td>14,0</td>
<td>3,1</td>
<td>5,6</td>
<td>2,94</td>
<td>1,37</td>
<td>0,16</td>
</tr>
<tr>
<td>B-14</td>
<td>Ilmenite</td>
<td></td>
<td>8,8</td>
<td>18,0</td>
<td>31,0</td>
<td>13,6</td>
<td>3,6</td>
<td>13,7</td>
<td>2,0</td>
<td>3,4</td>
<td>1,37</td>
<td>1,81</td>
<td>0,1</td>
</tr>
</tbody>
</table>
y = ax + b

(2)

where: y is the surface tension of the melt, mN/m, x - the temperature of the melt, °С, a and b - coefficients.

The interfacial tension at the boundary metal – slag and metal – coating was determined by the method of spreading of the drop of slag or coating on the surface of large droplets of molten metal, based on the calculation of interfacial tension by the surface tension of the respective phase boundary and the contact angle between them [6]:

\[ \sigma_{me-sl} = (\sigma_{me} - \sigma_{sl} \cdot \cos \theta) \cdot \sqrt{1 + \left( \frac{\sigma_{sl} \cdot \sin \theta}{\sigma_{me} - \sigma_{sl} \cdot \cos \theta} \right)^2} \]

(3)

where: \( \sigma_{me} \) is the surface tension of the metal at 1500°C, mN/m, \( \sigma_{sl} \) - the surface tension of the molten welding slag at 1500°C, mN/m, \( \Theta \) - regional contact angle between the molten phases, degree.

Similarly, for the “primary” slag:

\[ \sigma_{me-co} = (\sigma_{me} - \sigma_{co} \cdot \cos \theta) \cdot \sqrt{1 + \left( \frac{\sigma_{co} \cdot \sin \theta}{\sigma_{me} - \sigma_{co} \cdot \cos \theta} \right)^2} \]

(4)

where: \( \sigma_{co} \) is the surface tension of the melt coating of the electrode at 1500°C.

The installation diagram for determining the contact angle of the contact of the molten phases: 1 - the furnace, 2 - crucible with molten metal, 3 - a drop of slag, 4 - thermocouple, 5 - micro lift, 6 - alundum tube, 7 - camera.

Fig. 2. Installation diagram for determining the contact angle of the contact of the molten phases: 1 - the furnace, 2 - crucible with molten metal, 3 - a drop of slag, 4 - thermocouple, 5 - micro lift, 6 - alundum tube, 7 - camera.

The steel in an amount of 200 g was melted in the alundum crucible with a diameter of 40 mm in a horizontal furnace with a graphite heater. The relatively large diameter of the metal mirror made possible to neglect its curvature in the calculation of the interfacial tension.

For formation of drops of slag on the molten metal the alundum tube was brought to its surface with the use of a microscrew, through which the particles of welding slag or coating with a total mass of 0.6...0.8 grams were delivered. The tube was kept above the metal so low that slag or coating particles falling from top, were dwelled on the tube walls and when melting they did not fly down from the metal. As a result, the drop large enough was formed on the metal surface. After that the tube was lifted and the drop was photographed from a distance of 700 mm.

The photography was carried out in the furnace at temperature of 1500°С, which was controlled by the platinum-rhodium thermocouple and regulated with a potentiometer.

To protect the melt from exposure to the air Argon was supplied to the working zone of the furnace. The measurement of boundary angles of the contact was carried out by using the photographs.

RESULTS AND DISCUSSION

The dependencies of the surface tension on the temperature of the melts and coatings of electrodes and welding slag respectively are shown at Figs. 3 and 4.

The dependence of the surface tension of the melts of coatings of electrodes and welding slag from temperature and the values of surface tension and interfacial tension at 1500°C are given in Table 2.

As we can see on Fig. 3 and Table 2 that despite the different character of the dependence of the surface tension on the temperature of the molten coating \( \sigma_{co} \), the values \( \sigma_{me-co} \) at the temperature 1500°C is in a relatively narrow range for different electrodes. There were not determined any specific patterns for different groups of
electrodes as for the value $\sigma_{co}$ and $\sigma_{me-sl}$ at 1500°C, as for the temperature dependence of surface tension.

However, as it can be seen from Fig. 4, the welding slags on the value of $\sigma_{sl}$ and $\sigma_{me-sl}$ at 1500°C and temperature dependence of surface tension can be grouped into the same three groups (A, B, and C) as the corresponding electrodes.

It should be noted that at 1500°C the electrodes from group A the values of the $\sigma_{sl}$ are higher than the values $\sigma_{co}$, and $\sigma_{me-sl}$ is lower than $\sigma_{me-co}$. For all other experimental electrodes the reverse pattern is observed.

The “secondary” slags of the electrodes from Group B have the greatest surface tension. It can be probably attributed to the dominant influence of the high content of FeO and MnO, because according to one data source TiO$_2$ does not affect the surface tension of the melt, and according to other information it reduces it to the some extent [7, 8]. Within the group B the surface tension of “secondary” slags is increased with the rise of CaO content and decrease in K$_2$O concentration, which is consistent with the literature data.

Among the main electrodes the “secondary” slags of the electrodes of Group B containing the maximum amount whether CaO or MnO and FeO with low F-content have the greatest surface tension. These slags are also characterized by the highest content of Fe$_2$O$_3$, which causes an increase in surface tension with high concentrations of CaO.

The experiments show that among the based coated stick electrodes the highest surface tension of the molten welding slag is specific to the Group B. This evidently facilitates the downward welding, because the resultant slag under the action of surface forces is retained from flowing and does not prevent the welding process. The electrodes of the subgroup B form a welding slag with a minimum of interfacial tension. This probably determines the smooth formation of the weld, in particular, a penetration bead when welding of the root layer. This is verified by the following experimental data: the electrodes LB 26V, which ensure the downward welding without the formation of a weld bead, have a high value of $\sigma_{me-sl}$.

The low surface tension of “secondary” slags of electrodes of Group A is evidently determined by a relatively low CaO content and a high F content. The low surface tension of the slag electrodes LB52U with

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$\sigma_{co}$, mN/m

$\sigma_{sl}$, mN/m

**Fig. 3.** The dependence of the surface tension of the coatings of the electrodes on the temperature of the melt: 1 - Fox EV50, 2 - LB 26V, 3 - SSSI-13/55, 4 - B-14, 5 - OZS-4, 6 - WCC-4, 7 - LB86VS, 8 - LB52U, 9 - Philips 27P.

**Fig. 4.** Dependence of surface tension of welding slags on molten metal temperature: 1 - Fox EV50, 2 - LB 26V, 3 - SSSI-13/55, 4 - B-14, 5 - OZS-4, 6 - WCC-4, 7 - LB86VS, 8 - LB52U, 9 - Philips 27P.
little F content is achieved by maximum content of SiO$_2$ and K$_2$O and the almost complete absence of Fe$_2$O$_3$.

Based on the value of interfacial tension at the interface of melt metal and welding slag the electrodes are classified in the same groups as the surface tension “secondary” slag, as well as the type of coating and designation of electrodes.

It is known that the increased content of FeO, MnO, Na$_2$O and Fe$_2$O$_3$ in the slag have the greatest influence on the reduction of interfacial tension. It increases in $\sigma_{me-sl}$ content of MgO, CaO and especially Al$_2$O$_3$, and K$_2$O and TiO$_2$ slightly reduced it. The fluorides, if rather, reduce the interfacial tension, but at low concentrations (up to 10 %) they have little effect on it [9]. The change of SiO$_2$ content has a little effect on the value of $\sigma_{me-sl}$.

The analysis of data given in Table 2 shows that the minimum interfacial tension corresponds to the welding slags of electrodes of Group B which contain the maximum amount of FeO, MnO and Fe$_2$O$_3$.

Among the main “secondary” slags of electrodes of Group B the lowest value of $\sigma_{me-sl}$ is achieved due to the highest contents of Fe$_2$O$_3$, MnO, Na$_2$O and, partially, FeO. The more interfacial tension corresponds to the electrodes of Group B with less content of FeO and MnO. The “secondary” slags of electrodes of Group A give the maximum interfacial tension. They do not have or have precious few Fe$_2$O$_3$ content, as well, as a rule, a relatively little Na$_2$O and MnO. Among these slags, the greatest value of $\sigma_{me-sl}$ has a slag of electrodes LB52U containing the highest amount of Al$_2$O$_3$, and the lowest - slag of electrodes SSSI–13/55 containing the highest amount of Na$_2$O when low amount K$_2$O.

Table 2. Surface and interfacial tension of molten coatings of electrodes and welding slags.

<table>
<thead>
<tr>
<th>Group of electrodes</th>
<th>Electrode classification</th>
<th>Equations of the dependence of surface tension on temperature</th>
<th>$\sigma_{co}$ (mN/m)</th>
<th>$\theta$, degree</th>
<th>$\sigma_{me-co}$ (mN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coatings of electrodes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A'</td>
<td>SSSI-13/55</td>
<td>$\sigma_{co} = -0.22t + 598$</td>
<td>268</td>
<td>19.0</td>
<td>1050.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma_{co} = -1.31t + 2164$</td>
<td>204</td>
<td>21.0</td>
<td>1112.0</td>
</tr>
<tr>
<td>A''</td>
<td>LB52U</td>
<td>$\sigma_{co} = -0.256t + 584$</td>
<td>200</td>
<td>31.5</td>
<td>1134.3</td>
</tr>
<tr>
<td>B'</td>
<td>LB 26V</td>
<td>$\sigma_{co} = -0.507t + 980$</td>
<td>220</td>
<td>45.0</td>
<td>1155.4</td>
</tr>
<tr>
<td>B''</td>
<td>Philips 27P</td>
<td>$\sigma_{co} = -0.413t + 812$</td>
<td>192</td>
<td>26.5</td>
<td>1113.4</td>
</tr>
<tr>
<td></td>
<td>LB86VS</td>
<td>$\sigma_{co} = -0.271t + 609$</td>
<td>204</td>
<td>17.75</td>
<td>1107.5</td>
</tr>
<tr>
<td>C</td>
<td>WCC-4</td>
<td>$\sigma_{co} = -0.232t + 574$</td>
<td>226</td>
<td>28.0</td>
<td>1105.8</td>
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<tr>
<td></td>
<td></td>
<td>$\sigma_{co} = -0.28t + 652$</td>
<td>232</td>
<td>30.0</td>
<td>1111.3</td>
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<tr>
<td></td>
<td></td>
<td>$\sigma_{co} = -0.192t + 548$</td>
<td>260</td>
<td>15.25</td>
<td>1051.5</td>
</tr>
<tr>
<td></td>
<td>Coatings of electrodes</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>A'</td>
<td>SSSI-13/55</td>
<td>$\sigma_{s} = -0.3t + 670$</td>
<td>220</td>
<td>17.0</td>
<td>1091.5</td>
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<td></td>
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<td>$\sigma_{s} = -0.335t + 688$</td>
<td>185</td>
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<tr>
<td>A''</td>
<td>LB52U</td>
<td>$\sigma_{s} = -0.275t + 608$</td>
<td>195</td>
<td>35.0</td>
<td>1145.7</td>
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<tr>
<td>B'</td>
<td>LB 26V</td>
<td>$\sigma_{s} = -0.293t + 755$</td>
<td>315</td>
<td>42.5</td>
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<tr>
<td>B''</td>
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<td>$\sigma_{s} = -0.413t + 892$</td>
<td>272</td>
<td>27.0</td>
<td>1064.8</td>
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<tr>
<td></td>
<td>LB86VS</td>
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<td>1052.1</td>
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<tr>
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<td>$\sigma_{s} = -0.06t + 419$</td>
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<td>24.5</td>
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<td>$\sigma_{s} = -0.032t + 359$</td>
<td>311</td>
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<td>$\sigma_{s} = -0.024t + 372$</td>
<td>336</td>
<td>22.0</td>
<td>990.2</td>
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</tbody>
</table>

Notes:
1) $\sigma_{s}$ and $\sigma_{co}$ – the surface tension of melts of slag and coating, respectively;
2) $\sigma_{me-sl}$ and $\sigma_{me-co}$ – the interfacial tension of the melts of slag and coating, respectively.
CONCLUSIONS

The experiments show that among the based coated stick electrodes the Group B is characterized by the highest surface tension of the molten welding slag. This facilitates the downward welding because the resultant slag under the action of surface forces is retained from flowing and does not prevent the welding process. The electrodes of subgroup B” form a welding slag with a minimal interfacial tension. This probably determines the smooth formation of the weld, in particular a penetration bead when welding the root layer. This is verified by the following experimental data: the electrodes LB 26V which ensure the downward welding without the formation of a weld bead, have a high value of $\sigma_{\text{met-sl}}$.

In the development of based coated stick electrodes providing a guaranteed root penetration and the stable formation of the penetration bead when downward welding, the most promising is to obtain a welding slag with a low content of F and high content of MnO, FeO and Fe$_2$O$_3$ with the partial substitution of K$_2$O for Na$_2$O. It is necessary to reduce the surface tension of melts of coatings and enhance their interfacial tension; as well as to achieve a welding slag with a high surface tension and a low interfacial tension.

The key point in obtaining the necessary physical properties of the coatings and the slags is the composition (formulation) of coating of electrodes. The differences in physical properties of welding slags of different groups of based coated electrodes is primarily determined by the ratio of their carbonate-formed oxides and fluorine, and, consequently, carbonates and fluorides (mostly marble and fluorspar) in the coating of the respective electrodes. The difference of the physical properties of “primary” and “secondary” slags can be controlled by the introduction into the coating of the iron powder, which passes into the weld metal and provides the specific difference of the physical properties of melts, coating and welding slags of the same electrodes.

REFERENCES