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Assessment of welding engineering properties of basic type electrode coatings of different electrode manufacturers for welding of pipe parts and assemblies of heat exchange surfaces of boiler units

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ABSTRACT

Introduction. New grades of high-strength steels, machining and repair processes are being introduced in the power industry. At the same time manual arc welding remains the main technological process for equipment repair in conditions of thermal power plants. Welding materials used in equipment repair should provide comparable to the base metal mechanical properties of the weld. The welding industry has long faced the problem of high sensitivity of basic type electrodes to moisture absorption. High susceptibility to cold cracking caused by diffusible hydrogen and hydrogen embrittlement are major obstacles to the wider use of basic-type electrodes for high-strength steels. Hydrogen production during arc welding is the result of the presence of hydrogen in the arc atmosphere, hydrogen-contaminated filler material, or local hydrogen residues on the source material. During welding, molecular hydrogen is dislocated by the arc energy and then easily absorbed by the molten material. Currently, the welding materials market produces electrodes with basic coating of well-known and proven brands, various national and foreign manufacturers. However, in practice there are cases of cold cracks in the weld seam after welding. **Purpose of work** is to assess the welding and technological properties of basic type electrode coatings of different manufacturers. The work investigates specimens weld overlaid with electrodes *TMU-21U*, *TSU-5* of different manufacturers and the content of diffusion-mobile hydrogen in the weld overlaid metal is determined. The methods of research are mechanical static tensile tests, chemical composition analysis and metallographic studies. Determination of welding-induced hydrogen content can be accomplished by various quantitative elemental analysis methods. All test methods involve welding under defined conditions followed by deep freezing of the test specimens as quickly as possible. In this way, unintended diffusion processes are inhibited and the hydrogen introduced into the weld metal is retained. Subsequently, the diffusing hydrogen is desorbed from the test specimens in a controlled manner. **Results and Discussion.** An assessment of welding engineering properties of the electrodes revealed unstable arc burning. Mechanical properties of the welded metal of the investigated electrodes are at the minimum permissible level from the requirements of normative documents. The concentration of hydrogen present in the arc weld metal is multifactorially dependent on the welding procedure (process and parameters, consumables used, as well as environmental conditions (e.g. humidity). For qualitative assessment, hydrogen content of more than 15 cm^3/100 g is considered high and hydrogen content less than 5 cm^3 ml/100 g is considered very low. **Presented results.** The conducted evaluation of welding engineering properties of electrodes with basic coating showed satisfactory results. Mechanical properties of the welded metal in terms of impact toughness are at the lower permissible limit, relative elongation does not meet the requirements of normative documents. The content of diffusion-mobile hydrogen in the welded metal is higher than the declared indicators by the electrode manufacturers.

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Introduction

New energy policy has greatly contributed to the rapid increase in the share of renewable, clean energy such as wind, solar and hydropower. At the same time, thermal power plants still remain an important element in the production of electricity and heat. From year to year, regulatory requirements for the characteristics of steels, for welding and repair procedures for various machine parts and mechanisms of thermal power plants are growing. Traditionally, the main process of welding and repair at thermal power plants is manual arc welding (*MAW*) with coated electrodes, mechanized welding in shielding gases. The main consumables in accordance with the guidelines (*GL*) [1] for manual arc welding are electrodes of the basic type: *UONI-13/45*, *UONI-13/55*, *UONI-13/55S*, *LEZUONI-13/55*, *TMU-21U* etc. Control of the moisture content in the electrode coating is crucial for obtaining defect-free, high-quality welds when arc welding of steels in a protective environment [2].

The welding industry has long been faced with the problem of high sensitivity of basic type electrodes to moisture absorption [3, 4]. Moisture is the main source of hydrogen entering the weld pool. The presence of hydrogen in the melting zone when welding steels can be dangerous because it causes the formation of cold cracks, both in the heat-affected zone and in the melting zone, which cause catastrophic failure of the welded steel structure. Cold cracks caused by hydrogen are a serious problem in the weldability of low-alloy high-strength steels [2–7]. Cold cracks occur with the simultaneous existence of three factors: residual stresses after welding, brittle structures in the heat-affected zone (*HAZ*) and a high diffusive hydrogen content in the weld overlaid metal [2]. During welding, hydrogen absorbed in the weld zone has a high tendency to diffuse into the *HAZ*. The parameters that influence the diffusion of hydrogen from the weld zone into the welded product are temperature, metal microstructure, solubility, residual stresses and the effect of accumulation in metal defects.

It has been established that the main source of hydrogen in the weld metal during *MAW* is the electrode coating decomposition products [5, 8]. Before the hydrogen atoms dissolve in the liquid weld pool, H_2O and H_2 dissociate. The dissolution of molecular hydrogen in the weld pool increases with increasing partial pressure of the components of the gas mixture according to *Sieverts* law. One of the mechanisms of diffusion reduction of hydrogen is a decrease in the partial pressure of hydrogen in the atmosphere of the welding arc, for example, due to the dissociation of carbonates and fluorides, namely Na_2CO_3, NaF, $CaCO_3$, CaF_2, $MgCO_3$ and MgF_2. Carbonates dissociate to form CO_2 and CO, which reduces the partial pressure of hydrogen above the weld pool [5–11]. Decomposition of the basic type electrode coating, containing $CaCO_3$ as the main component (45–50 %), leads to the formation of gas protection with low hydrogen content. The second important component of the main type electrode coating is calcium fluoride CaF_2. The introduction of fluoride compounds into the composition of welding materials is one of the effective ways to reduce the absorption of hydrogen by liquid metal [5, 8, 9]. Fluorine atoms, combining with electrons, transform into ions with low mobility [10, 11]. This leads to a decrease in the conductivity of the arc gap and deterioration in the stability of the arc. However, fluorine atoms are able to bind hydrogen into HF molecules that do not dissolve in the weld pool, reducing the saturation of the weld metal with hydrogen [5]. Therefore, the use of a basic electrode coating is a key approach to reducing the risk of cold cracking when welding high-strength steels [12–14]. Although the electrode base coating is a low-hydrogen welding material, it is susceptible to moisture absorption when exposed to the atmosphere [5, 8, 14].

In Europe, the measurement of diffusive hydrogen in arc welded metal is regulated by the *ISO 3690* standard [15]. This standard is similar to the American standard *AWS A4.3-93* [16] and the Japanese *JIS Z 3113* [17]. There are differences in details; however, with respect to the methods described, the standards are largely equivalent. Welding electrodes are classified into groups depending on the diffusible hydrogen content electrodes can introduce into the weld metal by various national and international standards. The International Institute of Welding (*IIW*) uses a linear scale increment to measure hydrogen levels in units of 5 (5–10–15 ml/100 g), as well as a logarithmic scale (4–8–16 ml/100 g) used by *AWS*, based on the correlation of lower critical voltage, lower preheating temperature with diffusing hydrogen levels to avoid hydrogen cracking. The content of diffusion hydrogen in the weld overlaid metal depends not only on the composition (type) of the coating, but also on the calcination temperature of the electrodes [18]. According to Russian regulatory documents [18], the group with the *H5* index includes electrodes that provide a hydrogen content in the weld overlaid metal of up to 5 cm^3/100 g, in *H10* from 5 to 10 cm^3/100 g, in *H15* from 10 to 15 cm^3/100 g, and the most critical group over 15 cm^3/100 g. All electrode suppliers should adhere to the new marking of welding materials with a mandatory indication of the hydrogen content in the weld overlaid metal [18]. The manufacturer has a great responsibility for implementing appropriate hydrogen cracking protection measures in welding procedures. In addition to prescribing properly processed basic type welding consumables with low hydrogen content, manufacturers rely on preheating, temperature control between passes, strict control of heat input and post-welding heat treatment to reduce the risk of cracking during welding. These traditional hydrogen control measures are expensive and time-consuming.

According to the *ISO 3690* standard [15], various methods can be used to determine and measure hydrogen content: (1) the mercury method; two carrier gas methods: (2) gas chromatography (*CG*) and (3) hot extraction (*HE*). The mercury method is widely discussed critically [8, 14, 19–23], since the use of mercury is associated with health risks, as well as from the point of view of environmental protection. Consequently, it is increasingly being replaced by other safer methods [8, 14]. Using *CG* method, hydrogen is collected from a weld specimen in a closed chamber for a specified period of exposure at elevated temperatures. For this reason, collection time can be reduced to several hours [14]. After this, the chamber is purged with carrier gas and the gas mixture is transferred to the *CG* unit. Typically, a gas chromatograph consists of a heated column to separate individual gases. Separation is achieved by different retention time of the carrier gas and hydrogen due to interaction with the column wall. The *HE* method (regardless of the use of vacuum or carrier gas) is based on the thermal activation of hydrogen atoms in a solid specimen and subsequent thermal desorption. Recent discussions [13, 14, 19–23] on the standardization of hydrogen determination in welds according to *ISO 3690* [16] have shown that a discussion of experimental effects is necessary for the used method of carrier gas hot extraction (*CGHE*) from the point of view of a device for collecting and extracting hydrogen. In particular, important factors affecting the results of hydrogen extraction and collection are specimen temperature, extraction time, and its interdependencies. It is worth noting that additional boundary conditions may have an impact, for example, the size and surface of the specimen. All presented methods have advantages and disadvantages. It is also a matter of the available budget, as well as the number of specimens to be analyzed (and time per specimen), and what equipment is used to determine hydrogen in welds. Russia has adopted a standard for the determination of hydrogen in welds [24], which cannot always be used on industrial sites for operational control of welding materials. For the purpose of operational control in workshop conditions, the “pencil test” method is used [25], the advantage of which is the use of simple, inexpensive equipment, clarity and the ability to assess the effect on the kinetics of hydrogen evolution at negative temperature.

Thus, the growing demand for high-strength steels in the energy sector has led to an increased need for low-hydrogen welding technologies to reduce the risk of cold cracking. Therefore, moisture control of the base coating of the electrodes is the key to obtaining high-quality welds by observing handling conditions and storage methods to prevent moisture absorption, as well as calcining the electrodes at temperatures in the range of 340–400 °C [8].

The quality of the weld is influenced by the quality of the metal, which in turn is influenced by various factors of its production [26–36].

At the same time, the factor affecting the quality of the welded joint when using electrodes with a basic coating is the manufacturer of the welding electrodes itself. Currently, the market offers electrodes with a basic coating from various Russian and foreign manufacturers under the well-known brands *UONI*, *TMU*, etc., which do not always meet the requirements of regulatory documents on welding technological parameters [37–39], which poses a serious danger for use in conditions of thermal power plants. Replacing the recipe of the main components of the coating, failure to maintain the recipe, violations in the electrode production technology – all these factors can have an important impact on the quality of the weld [40, 41]. As consumers, we buy a ready-made product that externally complies with regulatory documents, but we can determine compliance with the claimed properties only after purchase and welding operation.

The ***purpose of the work*** is to determine the content of diffusion-mobile hydrogen in the weld overlaid metal made with electrodes with a basic coating from various manufacturers.

In this work, the main objective of the study was to evaluate the welding and technological properties of electrode coatings of the basic type from various manufacturers of electrodes for welding pipe parts made of low-alloy steels and assembly units of heat exchange surfaces of boiler units.

Materials and research methods

In this work, two brands of electrodes manufactured at different plants were compared, namely at *"Sudislavsky Welding Materials Plant", LLC*; imported electrodes manufactured by *ESAB*; and electrodes produced at *CJSC "Elektrodnyi zavod"*. Welding of the specimens was carried out with electrodes *TsU-5* and *TMU-21U* from three manufacturers: *CJSC "Elektrodnyi zavod"*, St. Petersburg and production of *"Sudislavsky Welding Materials Plant", LLC*, Kostroma region, Sudislavsky district, Tekotovo village, as well as the plant ESAB-SVEL, St. Petersburg on direct current of reverse polarity 90 A. The stability of the arc was determined using a welding parameters recorder *IRSP-11*, followed by computer processing of the results. Tests of welding and technological properties were carried out in accordance with the methodology described in *RD 03-613-03*, *GOST 9466* and *GOST 25616*. The content of chemical elements in the weld overlaid metal was determined according to *GOST 18895-75*, *GOST 28033-89* or using special methods that provide the required accuracy and reproducibility. Tests of the mechanical properties of the weld overlaid metal were carried out in accordance with the requirements of *RD 03-613-03*, *GOST R ISO 2560* and *GOST R ISO 15792-1*. The determination of diffusion hydrogen in the weld overlaid metal, taking into account the specifics of the energy enterprise Novo-Irkutsk Thermal Power Station, was determined directly in the repair shop using the "pencil test" method [25]. The specifics of repair welding under station conditions include welding at both positive and negative temperatures, and this greatly affects the process of hydrogen desorption from the weld [2, 4, 8]. Several sets of experiments were carried out to determine diffusion-mobile hydrogen using the "pencil test" method:

– the first set of experiments was carried out with non-calcined electrodes at room temperature, at about 18–20 ºC;

– the second set of experiments was carried out with electrodes after calcination at a temperature of 300–400 ºC for two hours at room temperature, at about 18-20 ºC;

– the third set of experiments was carried out when weld overlaying specimens at a negative temperature of −25 ºC using calcination;

– the set of experiments was carried out by weld overlaying specimens at a negative temperature of −25 ºC without calcination.

A *PICOTIG-180* welding machine from *EWM* was used for welding. Before welding, the electrodes were dried and calcined in a *PSPE10/400* furnace. The specimens were cleaned from the forming slag using a slag hammer and a metal brush, and an angle grinder *Dexter 800AG2-125.5*. Two plates made of steel *09G2C* with a size of 350×110 mm, 13 mm thick were welded with electrodes *TsU-5* and *TMU-21U*, calcined according to the manufacturer's recommendations indicated on the pack of electrodes (Table 1) for conducting research. Three specimens were welded, one specimen for each electrode of each manufacturer. The plates were made with cutting edges. The edges were prepared using milling. The edges prepared for assembly should be free of burrs, sharp transitions and sharp corners. Immediately before assembly, edges made for welding and adjacent areas of the surfaces of parts should be cleaned to a metallic shine and degreased. The width of the cleaned areas, counting from the cutting edge, should be at least 20 mm on the outside and at least 10 mm on the inside of the specimen (Fig. 1). Since the thickness of the plate is 13 mm, and the diameter of the electrodes is 3 mm, we weld in several layers of the weld. Each subsequent layer is processed with an abrasive tool using an angle grinder to avoid slag inclusions.

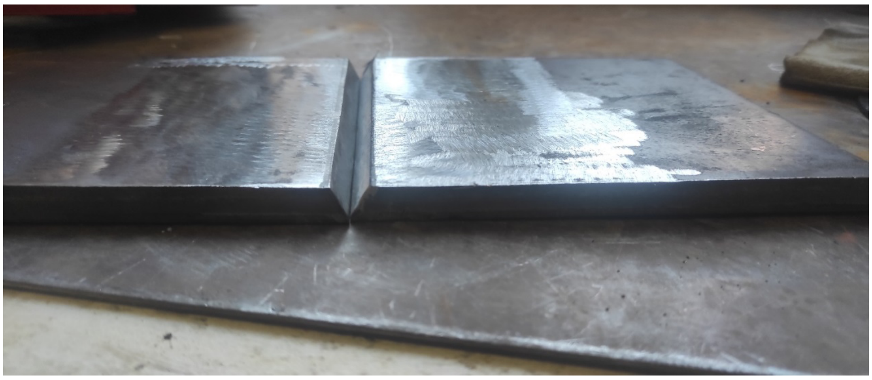


Fig. 1. Plates to be welded

Electrodes TMU-21U

Welding a specimen using electrodes produced by "*Sudislavsky Welding Materials Plant", LLC*

Before welding the test specimens, the electrodes were calcined in a furnace at a temperature of 350 ± 10 °C for an hour; this calcination mode is recommended by the manufacturer on the packaging of the electrodes. There was no index on the packaging for the hydrogen content in the weld overlaid metal according to the requirements [18]. After calcination, the electrodes were subjected to coating testing [1]. After lifting the electrode to a height of 1 meter, it was dropped in free fall onto a smooth steel plate.

Welding a specimen with electrodes produced by *CJSC "Elektrodnyi zavod"*.

Before welding the test specimens, the electrodes were calcined in a furnace at a temperature of 400 ± 20 °C for an hour; this calcination mode is recommended by the manufacturer on the packaging of the electrodes. There was no index on the packaging for the carbon content according to the requirements [18]. Note that the calcination mode differs from the electrodes produced by *"Sudislavsky Welding Materials Plant", LLC*. After calcination, the electrodes were subjected to coating testing. After lifting the electrode to a height of 1 meter, it was dropped in free fall onto a smooth steel plate.

Welding a specimen with electrodes produced by ESAB-SVEL.

Before welding the test specimens, the electrodes were calcined in a furnace at a temperature of 359–400 ± 20 °C for two hours; this calcination mode is recommended by the manufacturer on the packaging of the electrodes (see Fig. 6), and the hydrogen index is also indicated in the range from 5 to 10 cm^3/100 g. Note that the calcination mode differs from the electrodes produced by "*Sudislavsky Welding Materials Plant", LLC* and *CJSC "Elektrodnyi zavod"*.

Research results

Electrodes TMU-21U. Welding a specimen using electrodes produced by "Sudislavsky Welding Materials Plant", LLC

The results of the electrode coating quality tests were examined under a magnifying glass. Chipping of the coating was normal, partial with a total length of less than 5 % of the length of the coated part of the electrode, and also amounted to no more than 20 mm.

Before welding, a "fingernail" check was also carried out [1]. Three electrodes were randomly selected from the test package for testing and melted in a vertical position with an angle of inclination of the electrode to the seam of 50–60°. The size of the "fingernail" was measured from the end of the electrode rod to the most distant part of the melted coating (Fig. 2). The formation of a "fingernail" from the coating with a size of more than 3 mm and the falling off of pieces of non-melted coating from the rod are signs of a defect. Checking for the "fingernail" showed the presence of a non-melted coating of more than 3 mm, which is already a sign of a defect.

During welding of the specimens, there was unstable arcing a in all three layers: root, filling and facing. Also, after welding the root seam, the electrodes were re-calcined, but this did not give positive results for stable arcing. The specimen was assembled on a flat surface. A gap of 2 mm was set using welder's gauge

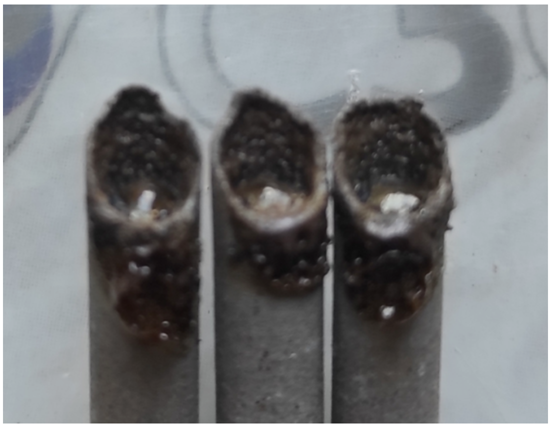
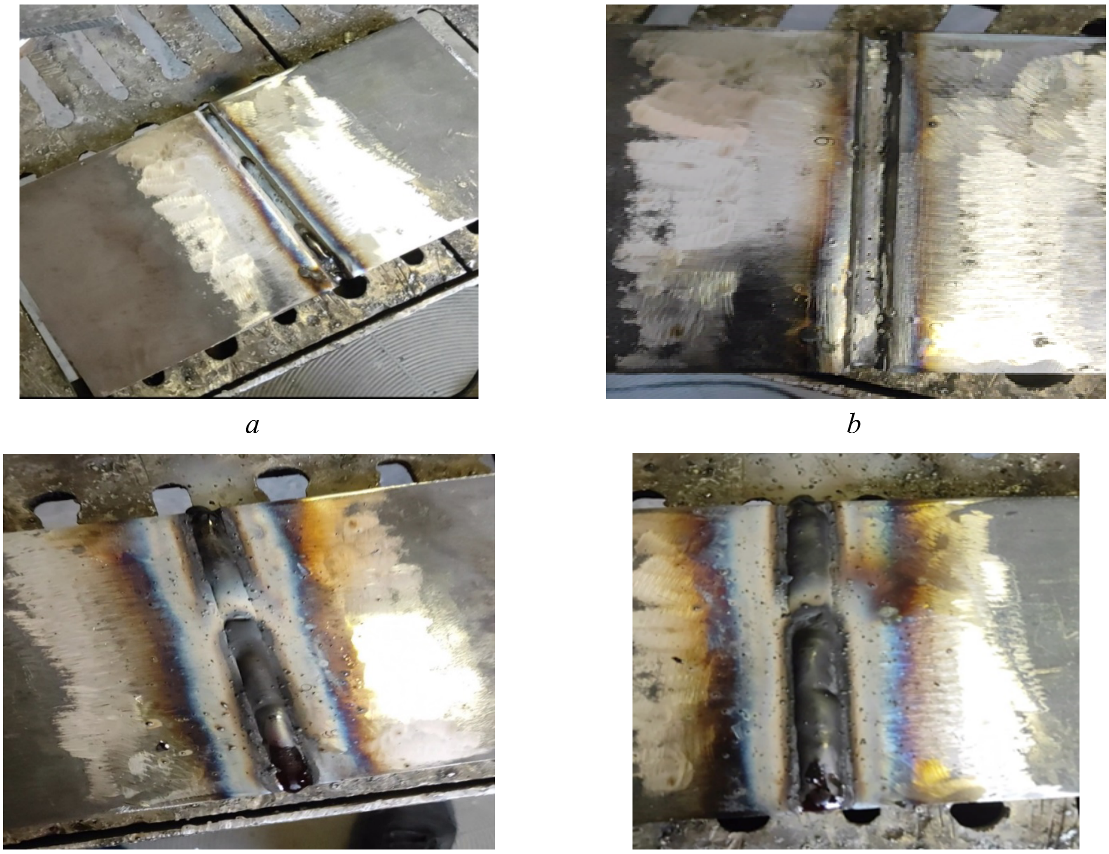


Fig. 2. Formation of a fingernail after welding on *TMU-21U* electrodes produced by *"Sudislavsky Welding Materials Plant", LLC*

UShS-3. The root seam was welded without separation using a reverse polarity welding current of 90 A (see Fig. 3, *a, b*). The next layer of the weld is the filling layer. Welding was carried out with a welding current of reverse polarity 90 A, as when welding the root weld. It took two electrodes to fill, which allows us to conclude that welding was carried out with separation (see Fig. 3, *c*). As can be seen from the photo of the root weld (see Fig. 3, *a*) there is no sputtering of metal on the specimen; slag is difficult to remove only after cooling using an angle grinder (see Fig. 3, *b*). When welding the filler layer, excessive spattering of molten metal is visible. Removing flash spatter using a welder's hammer is difficult. Flash sputter and slag after welding can only be removed mechanically. Before welding the facing seam, the specimen was completely cleaned of flash sputter. When making a facing seam, as well as during the root and filling seams forming, there was unstable arcing. The facing seam required 3 electrodes (see Fig. 3, *d*). As in the case of the filling layer of the seam, welding was carried out with a separation between electrode replacements. The current parameters were the same as in the case of welding the root and filling layers of the seam. On the facing seam, as well as on the filling seam, a fairly large amount of sputtering is visible, which is also a signs of a defect. The flash sputter was removed in preparation for further testing for the mechanical properties of the weld overlaid metal using only an angle grinder. The slag on the facing seam was removed with difficulty using a welder's hammer, since the impact of an angle grinder on the facing layer of the weld seam is prohibited.



a *b*

c *d*

Fig. 3. Appearance of the welded seam after filling with *TMU-21U* electrodes:
a – the root of the seam; *b* – the root of the seam after stripping with a machine;
c – the filling seam; *d* – the facing seam

Welding a specimen using electrodes produced by CJSC "Elektrodnyi zavod".

The results of the electrode coating quality tests were examined under a magnifying glass. Chipping of the coating was also normal, partial with a total length of less than 5 % of the length of the coated part of the electrode, and also amounted to no more than 20 mm.

Before welding, a "fingernail" check was also carried out [1]. The "fingernail" test was carried out in the same way as with electrodes produced by *"Sudislavsky Welding Materials Plant", LLC*; three electrodes were randomly selected from the test package for testing and melted in a vertical position with an angle of inclination of the electrode to the seam of 50–60°. The size of the "fingernail" was measured from the end of the electrode rod to the most distant part of the melted coating. The formation of a "fingernail" from the coating with a size of more than 3 mm and the falling off of pieces of non-melted coating from the rod are signs of a defect. Checking for the "fingernail" showed the presence of a non-melted coating of more than 3 mm, which is already a sign of a defect; the size of the "fingernail" on the other two electrodes was within tolerance and was less than 2.5 mm (Fig. 4).

Fig. 4. Formation of the fingernail after welding with *TMU-21U* electrodes *CJSC "Elektrodnyi zavod" St. Petersburg*

After identifying the "fingernail" we proceed to welding the specimens. During welding, there was unstable arcing in all three layers: root, filling and facing. Also, after welding the root seam, the electrodes were re-calcined, but this did not give positive results for stable arcing. The specimen was assembled on a flat surface. A gap of 2 mm was set using welder's gauge *UShS-3*. The root seam was welded without separation using a reverse polarity welding current of 90 A (see Fig. 5, *a*).

As can be seen from the photo of the root seam (see Fig. 5, *a*) there is no spattering of metal on the specimen; slag is difficult to remove only after cooling using an angle grinder. The next layer of the weld is the filling layer. Welding was carried out with the same current parameters as when welding the root seam. It took two electrodes to fill, which allows us to conclude that welding was carried out with separation (see Fig. 5, *b*). When welding the filler layer, excessive spattering of molten metal is visible. The flash sputter is larger than when welding with electrodes produced by *"Sudislavsky Welding Materials Plant", LLC*. Removing flash spatter using a welder's hammer is difficult. Flash sputter and slag after welding can only be removed mechanically.

Before welding the facing seam, the specimen was completely cleaned of flash sputter. When making a facing seam, the arc, as well as during the root and filling seams forming, burned unstable. The facing seam required 3 electrodes (see Fig. 5, *c*). As in the case of the filling layer of the seam, welding was carried out

a *b* *c*

Fig. 5. Appearance of the welded seam after filling with *TMU-21U* electrodes *CJSC "Elektrodnyi zavod" St. Petersburg*:

a – the root of the seam; *b* – the filling seam; *c* – the facing seam with a separation between electrode replacements. The current parameters were the same as in the case of welding the root and filling layers of the seam. On the facing seam, as well as on the filling seam, a fairly large amount of sputtering is visible, which is also a signs of a defect. At the same time, spattering was less than when using electrodes manufactured by *"Sudislavsky Welding Materials Plant", LLC*. The flash sputter was removed in preparation for further testing for the mechanical properties of the weld overlaid metal using only an angle grinder. The slag on the facing seam was removed with difficulty using a welder's hammer, since the impact of an angle grinder on the facing layer of the weld seam is prohibited. At the same time, slag was removed much easier than when using electrodes manufactured by *"Sudislavsky Welding Materials Plant", LLC.*

Welding a specimen using electrodes produced by ESAB-SVEL

The hydrogen index is indicated on the pack in the range from 5 to 10 cm^3/100 g (Fig. 6). Note that the mode of calcination of *ESAB-SVEL* electrodes differs from the mode recommended for calcining electrodes manufactured by *"Sudislavsky Welding Materials Plant", LLC* and *CJSC "Elektrodnyi zavod"*.

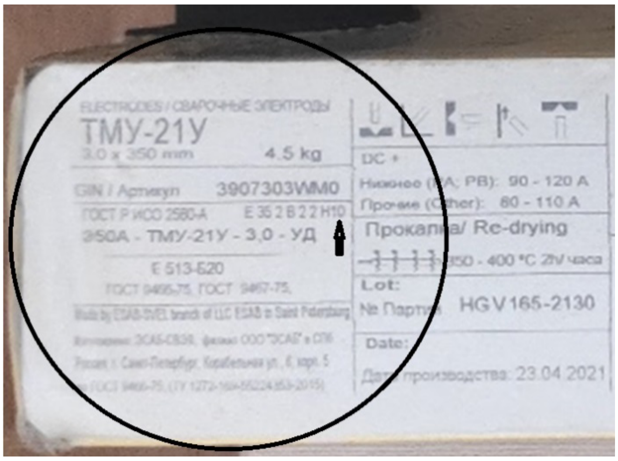


Fig. 6. Information provided by the manufacturer on the package

Fig. 7. Formation of the fingernail after welding after welding with *TMU-21U* electrodes *ESAB-SVEL, St. Petersburg*

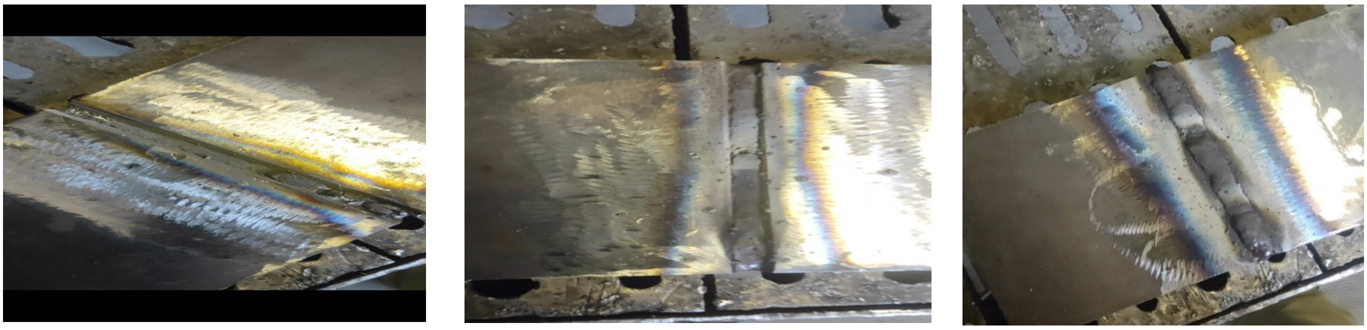
The results of the electrode coating quality tests were examined under a magnifying glass. No chipping of the coating was detected, although partial chipping of the coating with a total length of less than 5 % of the length of the coated part of the electrode is allowed, and also amounted to no more than 20 mm.

The "fingernail" (Fig. 7) test was carried out in the same way as with electrodes produced by previous manufacturers; three electrodes were randomly selected from the test package for testing and melted in a vertical position with an angle of inclination of the electrode to the seam of 50–60°. The size of the "fingernail" was measured from the end of the electrode rod to the most distant part of the melted coating. The formation of a "fingernail" from the coating with a size of more than 3 mm and the falling off of pieces of non-melted coating from the rod are signs of a defect. The size of the "fingernail" was within tolerance and was less than 2 mm. During welding of the specimens, the arc burned stably on the root and filling layers of the weld; on the facing seam, unstable burning of the seam was observed, which caused uneven formation of flakes.

After identifying the "fingernail" we proceed to welding the specimens. During welding, there was stable arcing in the root and filling layers of the weld; on the facing seam, unstable arcing was observed, which caused uneven formation of flakes.

The specimen was assembled on a flat surface. A gap of 2 mm was set using welder's gauge *UShS-3*. The root seam was welded without separation using a reverse polarity welding current of 90 A (see Fig. 8, *a*).

As can be seen from the photo of the root seam (see Fig. 8, *a*) there is no spattering of metal on the specimen; slag is difficult to remove only after cooling using an angle grinder. The next layer of the weld is the filling layer. Welding was carried out with the same current parameters as when welding the root seam. It took two electrodes to fill, which allows us to conclude that welding was carried out with separation (see Fig. 8, *b*). When welding the filler layer, a minimal amount of spattering of molten metal is visible. Removing flash spatter using a welder's hammer is easy. Slag after welding can only be removed mechanically.



a *b* *c*

Fig. 8. Appearance of the welded seam after filling with *TMU-21U* electrodes *ESAB-SVEL St. Petersburg*: *a* – the root of the seam; *b* – the filling seam; *c* – the facing seam

Before welding the facing seam, the specimen was completely cleaned of flash sputter. When making a facing seam, the arc, as well as during the root and filling seams forming, burned unstable. The facing seam required 3 electrodes (see Fig. 8, *c*). As in the case of the filling layer of the seam, welding was carried out with a separation between electrode replacements. The current parameters were the same as in the case of welding the root and filling layers of the seam. On the facing seam, as well as on the filling seam, a fairly large amount of sputtering is visible, which is also a signs of a defect. At the same time, flash sputter was removed from the specimen using a welder's hammer and a metal brush. The slag on the facing seam was easily removed using a welder's hammer. Preparation for further testing for the mechanical properties of the weld overlaid metal was carried out only with the help of an angle grinder.

Similar work was carried out for *TsU-5* electrodes. The results for determining the "fingernail" are negative for the specimens using electrodes produced by *"Sudislavsky Welding Materials Plant", LLC*. The welding engineering properties of the studied electrodes are presented in Table 1. The assessment was carried out on a five-point scale [1]. The results of determining the chemical composition and mechanical properties of the weld overlaid metal are given in Tables 2–7.

The results of experiments to determine diffusion-mobile hydrogen in the weld overlaid metal are presented in Figs. 9 and 10 for positive temperatures without calcination and with calcination of the electrodes, respectively. A comparative analysis of the diagrams shows that electrodes after calcination produce much less diffusion hydrogen in the weld overlaid metal, which is an indicator of a high-quality weld. The results of assessing the effect of negative temperatures on the desorption of hydrogen from the weld overlaid metal are presented in Figs. 11–14. The total content of diffusion-mobile hydrogen in the weld overlaid metal without calcination of the electrodes when the condition is maintained at −25 °C for 3 days, followed by moving the eudiometers to a warm room and holding for 3 days is shown in Figs. 11–14.

Table 1

Welding engineering properties of electrodes

Electrode brand, manufacturer	Arc excitation	Sputtering	Removability of slag	Bead forming	Sustained arc burning	Fingernail	Presence of defects on the surface
TMU-21U Sudislavskiy plant of welding consumables	4	strong	3	4	3	Out of tolerance	–
TMU-21U St. Petersburg	4	slight	3	4	3	Within tolerance	–
TMU-21U ESAB	4.5	moderate	4	4	4	Within tolerance	–
CU-5 Sudislavskiy plant of welding consumables	3	slight	3	4	4	Out of tolerance	–
CU-5 St. Petersburg	4	slight	3	3	4	Out of tolerance	–
CU-5 ESAB	4	slight	5	4	5	Within tolerance	–

Table 2

Chemical composition of weld overlaid metal by *TMU-21U* electrodes, *St. Petersburg*

Indicator name	*ND* value	Actual value	Accuracy	*ND* for test methods
Carbon, wt. %	0.08	0.12	0.016	*GOST 22536.1–89*
Silicon, wt. %	0.28	0.26	0.03	*GOST 28033–89*
Manganese, wt. %	0.82	0.68	0.04	*GOST 28033–89*
Phosphors, wt. %	0.023	0.019	0.003	*GOST 28033–89*
Sulfur, wt. %	0.009	0.01	0.004	GOST 28033–89

Table 3

Mechanical properties of weld overlaid metal with *TMU-21U* electrodes, *St. Petersburg*

No.	Indicator name	The value according to *GOST 380-2005*	Actual value	*ND* for test methods
1	Yield strength $\sigma_{0.2,}$ N/mm^2	≥235	205, 265, 249	*GOST 1497–84*
2	Ultimate tensile strength σ_u, N/mm^2	360–460	346, 378, 440	
3	Ultimate elongation δ, %	≥27	24, 24, 28	
4	Impact toughness *KCU*, J/cm^2	≥49	49, 51, 50	*GOST 9454–78*

Table 4

Chemical composition of weld overlaid metal with *TMU-21U* electrodes, *ESAB*

Indicator name	*ND* value	Actual value	Accuracy	*ND* for test methods
Carbon, wt. %	0.09	0.09	0.016	*GOST 22536.1–89*
Silicon, wt. %	0.30	0.29	0.03	*GOST 28033–89*
Manganese, wt. %	0.85	0.80	0.04	*GOST 28033–89*
Phosphors, wt. %	max 0.030	0.022	0.003	*GOST 28033–89*
Sulfur, wt. %	0.009	0.012	0.004	GOST 28033–89

Table 5

Mechanical properties of weld overlaid metal with *TMU-21U* electrodes, *ESAB*

No.	Indicator name	The value according to *GOST 380–2005*	Actual value	*ND* for test methods
1	Yield strength $\sigma_{0.2,}$ N/mm^2	≥235	205, 265, 249	*GOST 1497–84*
2	Ultimate tensile strength σ_u, N/mm^2	360–460	346, 378, 440	
3	Ultimate elongation δ, %	≥27	24, 24, 28	
4	Impact toughness *KCU*, J/cm^2	≥49	49, 51, 50	*GOST 9454–78*

Table 6

Chemical composition of weld overlaid metal with electrodes *TMU-21U*, *"Sudislavsky Welding Materials Plant", LLC*

Indicator name	*ND* value	Actual value	Accuracy	*ND* for test methods
Carbon, wt. %	0.08	0.12	0.016	GOST 22536.1–89
Silicon, wt. %	0.28	0.54	0.03	GOST 28033–89
Manganese, wt. %	0.82	1.37	0.04	GOST 28033–89
Phosphors, wt. %	0.023	0.013	0.003	GOST 28033–89
Sulfur, wt. %	0.009	0.011	0.004	GOST 28033–89

Table 7

Mechanical properties of weld overlaid metal with electrodes *TMU-21U*, *"Sudislavsky Welding Materials Plant", LLC*

No.	Indicator name	The value according to *GOST 380-2005*	Actual value	*ND* for test methods
1	Yield strength $\sigma_{0.2,}$ N/mm^2	≥235	225, 285, 260	*GOST 1497–84*
2	Ultimate tensile strength σ_u, N/mm^2	360–460	315, 395, 390	
3	Ultimate elongation δ, %	≥27	21, 21, 25	
4	Impact toughness *KCU*, J/cm^2	≥49	45, 42, 50	*GOST 9454–78*

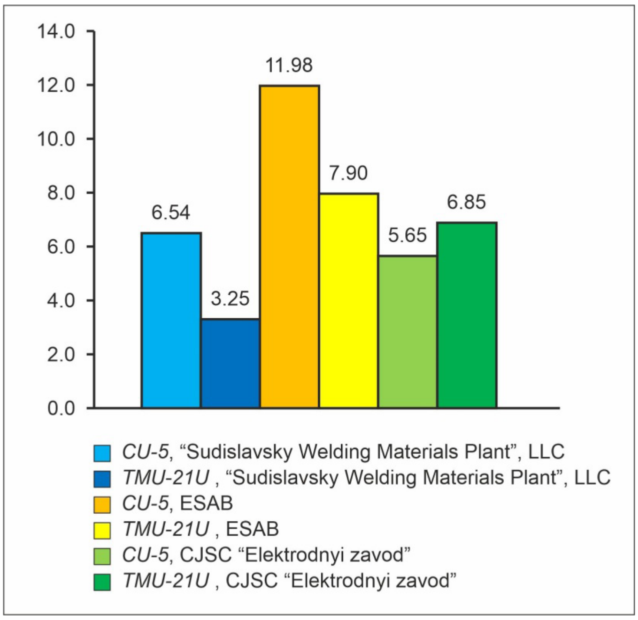


Fig. 9. The content of diffusible hydrogen in the weld overlaid metal at ambient temperature 20 °C, welding with electrodes from a new bundle without hardening

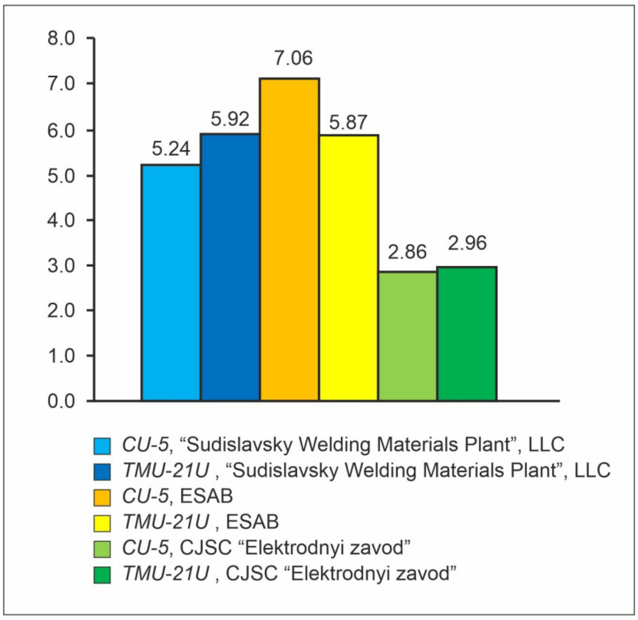


Fig. 10. The content of diffusible hydrogen in the weld overlaid metal at ambient temperature 20 °C, welding with tempered electrodes according to the manufacturer’s recommendation on the package

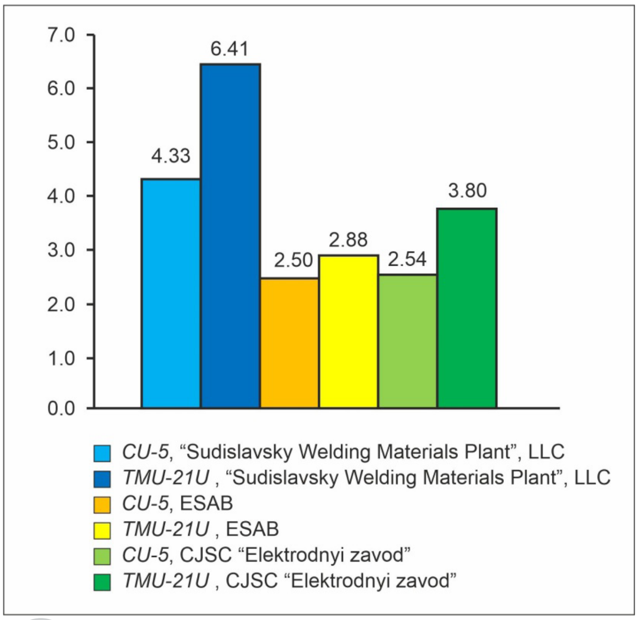


Fig. 11. The content of diffusible hydrogen in the weld overlaid metal without hardening at −25 °C for 3 days

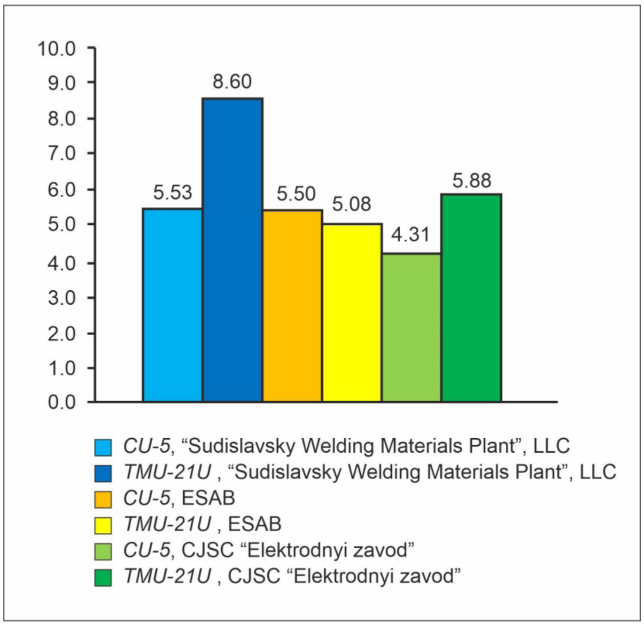


Fig. 12. The total content of diffusible hydrogen in the weld overlaid metal without hardening of electrodes at holding in conditions −25 °C for 3 days with subsequent moving of eudiometers to a warm room and holding for 3 days

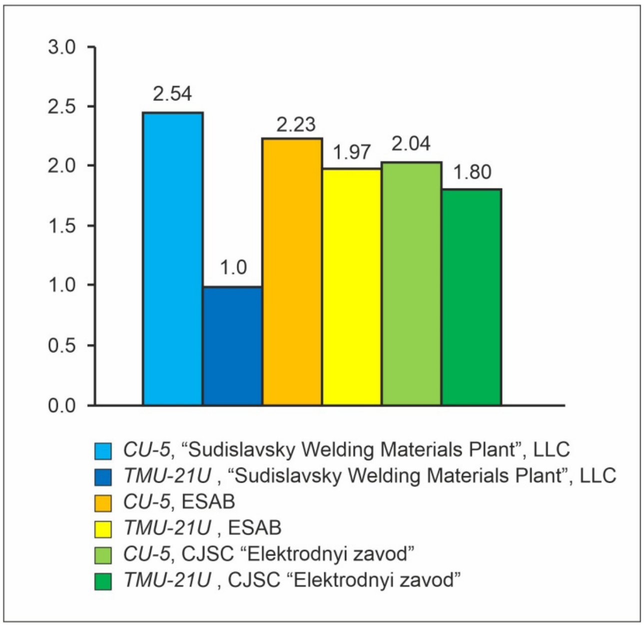


Fig. 13. The content of diffusible hydrogen in the weld overlaid metal with electrode hardening when aged at −25 °C for 3 days

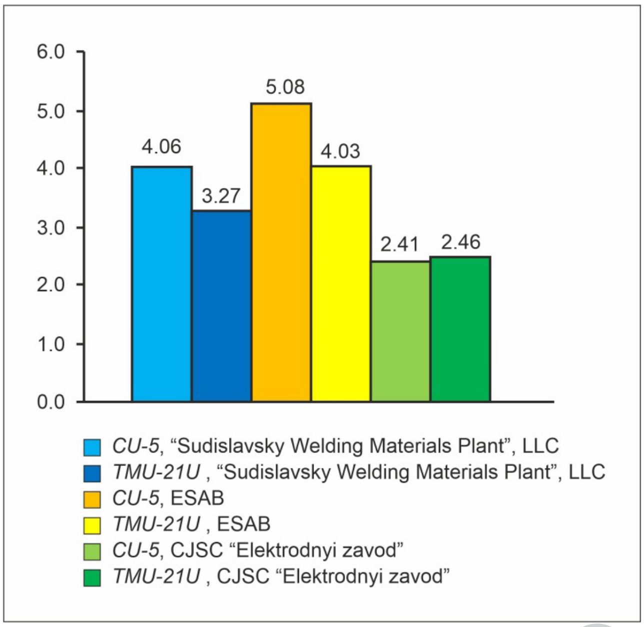


Fig. 14. The total content of diffusible hydrogen in the weld overlaid metal with electrode hardening during holding at −25 °C conditions for 3 days with subsequent moving of eudiometers to a warm room and holding for 3 days

The discussion of the results

It is known that the composition of the coating significantly affects the chemical composition of the weld metal, facilitating the transfer of elements into the welds, and thereby adding alloying elements to the weld zone. The behavior of weld overlaid metal is influenced by some physical-chemical and thermophysical characteristics of the components of the electrode coating [6–8]. The results presented above show that despite the standardization of components in the electrode coating of the well-known brands *TMU-21U*, *TsU-5*, the welding engineering properties, depending on the manufacturer, differs significantly; the coating melts unevenly, as shown by experiments to determine the "fingernail" (Figs. 2, 4, 7). The coatings under study belong to the basic type. During the experiments, it was noted that the main violation in stable arcing is associated with the process of droplet formation and its transfer. Due to the short length of the arc, the arc is shunted by a drop and goes out. Visually, this process is fast and difficult to record. The use of a welding process recorder made it possible to establish this effect of arc gap shunting for all studied electrodes. In this regard, in Table 1, in the column of stable arcing, scores are given in the range from 3 to 5 points. *TsU-5* ESAB electrodes demonstrated stable arcing.

An important physical parameter is the separation of slag from the weld metal. To ensure high welding productivity, good slag release is necessary because no additional time is required for the mechanical removal of slag adhering to the weld metal. In addition, in multi-pass welding, easily removable slag is critical to prevent any contamination of subsequent welding passes due to residual slag added to the weld pool [4, 5, 8]. The main reasons for good slag separation can be the following: providing a large difference in thermal expansion between the solid slag and the weld metal; preventing the formation of excess amounts of refractory phases such as spinel ($MgO\ Al_2O_3$), Cr_2O_3 or perovskite ($CaTiO_3$); preventing the formation of a chemical bond due to the formation of layers between the slag and the weld metal; ensuring the formation of low-strength slag from molten flux.

The coating of the basic type electrode, during melting leads to the release of gases that protect the molten weld pool from environmental impurities and help maintain stable arcing. CaO is added to increase the basicity of the flux and reduce the hydrogen content of the weld metal. It also reduces toughness and improves stable arcing, resulting in improved weld quality and mechanical properties. The main source of CaF_2 is calcium fluoride, which reduces the density and melting point of flux mixtures. It also increases the fluidity of the molten metal and removes hydrogen from the molten pool, forming hydrogen fluorides.

One of the problems that emerged when testing electrodes is the poor separability of slag from the weld overlaid metal, which seriously affects productivity. The appearance of the weld beads before and after removal of coated slag is shown in Figs. 3, 5, 8. During the experiments, it was seen that the color of the coated slags changed from dark blue to dark brown and then light brown; the surface of the weld changed from small ripples to large ones and the slag detachability became worse. It should also be noted that the dark blue slag tended to flake off in large chunks from the weld metal, while the brown slag would break into small pieces when the weld bead was knocked out and leave some slag stuck to the surface of the weld metal.

In appearance, when observing the destroyed slags, it was recorded that the slag of the *TsU-5* electrodes produced by *CJSC "Elektrodnyi zavod"*, was very dense and upon visual inspection there were no visible pores. However, slags of the *TsU-5* electrodes from other manufacturers had visually observable porosity. These observations indicated that slag detachability deteriorates as slag porosity increases.

It is known [4, 5, 8] that the separability of slag is very closely related to both the physical and chemical properties of the welding flux after melting the electrode coating [4–8]. One of the mechanisms of slag adhesion to the weld metal is a chemical bond due to the formation of a thin layer of oxides of metal phase elements on the surface of the weld metal [6]. This chemical bond can be weakened or eliminated by using a slag system with minimal oxidizing capacity (for example, a basic flux system) [4–6]. The separability of slag is affected by differences between the thermal expansion coefficients of slag and weld metal, as well as phase transformations in the slag during cooling [8].

Answering the question why, with a standardized ratio of components, different slag separability is recorded in standard electrode brands, but produced by different manufacturers, we postulate that slag separability depends on the weld metal/slag interface and the difference in the thermophysical properties of metal and slag. As a rule [4–12], a clear metal/slag interface corresponds to good slag separation, otherwise a blurred interface undoubtedly corresponds to poor slag separation. As the basicity of the slag increased, the oxidizing ability of the slag decreased. Since SiO_2, $CaCO_3$ and CaF_2 form the basis of the basic type of electrode coating, these same components are typical alkaline compounds [5], and SiO_2 is a strong acid oxide, the ratios $(CaO + CaF_2)/SiO_2$ directly indicate the basicity index [5, 8]. $CaCO_3$, CaF_2 and SiO_2 form the basis of the basic type of electrode coating, but the first two components are typical alkaline compounds [5], and SiO_2 is a strong acid oxide, and the ratios $(CaO+CaF_2)/SiO_2$ directly indicate the basicity index [5, 8]. Therefore, with an increase in the ratio $(CaO + CaF_2)/SiO_2$, the oxidizing ability of the slag decreases, i.e. the tendency to form a chemical bond decreases (slag separation increases). Obviously, in the case of the electrodes under study, the oxidizing ability does not decrease, which affects the separability of the slag and indicates to us a violation of the component ratios $(CaO + CaF_2)/SiO_2$ in the manufacture of electrode coatings *TMU-21U*, *TsU-5*.

In the course of the research, it was established that there is a difference in the chemical composition of the weld overlaid metal and the mechanical properties of *TMU-21U* electrodes from different manufacturers, which does not allow in practice to guarantee high quality indicators of the weld. A detailed analysis of the issue of guaranteed properties revealed a discrepancy between regulatory requirements, the characteristics of the electrodes posted on the manufacturers' website and the actual chemical and mechanical properties of the deposited metal. Manufacturers of welding electrodes indicate on the website and packaging chemical and mechanical properties taken from regulatory documents. The hardness of the weld overlaid metal is not the main indicator of electrodes, but even for one brand it differs greatly from different manufacturers. So, for example, for *TMU-21U* electrodes produced by *"Sudislavsky Welding Materials Plant", LLC*, the hardness is 224–238 NB, for the same electrodes, but produced by *CJSC "Elektrodnyi zavod"*, the hardness is only 168–179 NB, for *TMU-21U* electrodes produced by the *ESAB* plant, the hardness is 202–210 NB.

Failure to meet the standard indicators for the relative elongation of all electrodes under study, and the minimum permissible values of impact strength do not provide the necessary high mechanical properties, good fracture toughness at low temperatures for parts of power equipment according to the requirements [1].

An assessment of diffusion-mobile hydrogen in the weld overlaid metal showed that the manufacturers of *TMU-21U*, *TsU-5* electrodes: *CJSC "Elektrodnyi zavod"* and *"Sudislavsky Welding Materials Plant", LLC*, do not inform the real consumer according to the requirements [18] on the hydrogen content in the weld overlaid metal. The next question is the calcination modes of electrodes of the same brand from different manufacturers differ in the direction of increasing the calcination temperature. In the present study, the level of diffusible hydrogen varies greatly in all cases considered. Figs. 9, 10 show the content of diffusion-mobile hydrogen in the weld overlaid metal at an ambient temperature of 20 °C. No significant differences in hydrogen content were recorded; all of them fall into the group from 5 to 10 cm^3/100 g. The minimum level of diffusion hydrogen was measured for electrodes *TMU-21U*, *TSU-5* of *CJSC "Elektrodnyi zavod"* (Tables 4–5).

During bead forming, hydrogen absorbed by the weld overlaid metal (weld zone) has a high tendency to diffuse into the HAZ. The parameters affecting the diffusion of hydrogen in the weld overlaid metal depend on temperature, residual stress, solubility, metal microstructure and trapping effect.

It is important to understand that there are significant differences in strength and microstructure between different grades of pipeline steel and the behavior of hydrogen penetration into its welds is completely different. For example, for low alloy steels of strength grade X52 for pipes, it contains polygonal ferrite and some pearlite, while the weld for steels of strength grade X52 consists of polygonal ferrite, some carbide particles and acicular ferrite particles. Chaotically distributed carbide particles reduce hydrogen diffusion, resulting in welds of both low and high strength steels having lower hydrogen diffusion than base steels [4, 5]. Additionally, the weld metal when welding low alloy steel contains less acicular ferrite, resulting in the weld having a lower hydrogen penetration rate than the base steel, while a high strength steel weld typically has a higher hydrogen penetration rate than high strength steel weld and base steel.

As stated earlier, hydrogen atoms from several sources can enter the molten weld pool and remain in the weld zone [8]. The microstructure of welds mainly contains ferrites, such as acicular ferrite and polygonal ferrite. Ferrite typically forms a crystallographic plane (1 0 0), where the energy barrier for hydrogen absorption is 0.38 eV, which is significantly lower than the energy barrier of 1.02 eV at a crystallographic plane (1 1 0) of bainite found in high-strength base steels. [4–8]. Moreover, non-metallic inclusions, such as *Si*/*Al*-*O* inclusions contained in welds, are irreversible hydrogen traps and effectively trap mobile hydrogen in the crystal lattice [4, 5]. The higher hardness of the inclusions than the base steel causes lattice distortion where the concentration of stress or strain further promotes hydrogen trapping. The accumulation of hydrogen leads to the formation of hydrogen gas molecules, which leads to an increase in local pressure (voltage). Then, hydrogen can reduce the adhesive force between iron atoms. All of it contribute to the initiation of microcracks and its propagation, and delayed brittle fracture in welds.

The values of diffusion-mobile hydrogen after storage at negative temperatures are of interest (Figs. 11–14). It is generally accepted that grain boundaries and phase boundaries can serve as effective hydrogen traps, collecting and accumulating hydrogen atoms. However, it was found that the diffusion coefficient of hydrogen along solid grain boundaries is six orders of magnitude higher than inside grains [5, 8]. From our experiments it is clear that negative temperatures slow down the diffusion of hydrogen and contribute to its localization and increase in local pressure (stress), which increases the likelihood of cracking of the weld. Compared to other measures, controlling diffusible hydrogen is more effective in reducing the tendency for hydrogen to accumulate. One of the main sources of hydrogen released during welding is air moisture and hydrogen-containing welding electrodes. Mandatory calcination of the electrodes can effectively reduce the ingress of hydrogen into welds. The use of moisture-resistant coatings and optimization of arc welding parameters make it possible to control the hydrogen content. However, welding electrodes are usually prone to absorbing moisture. Reducing the cooling rate of the weldment by increasing the heat input can give hydrogen more time to diffuse out of the welds, reducing the hydrogen content.

Conclusion

In this work, the main objective of the study was to compare the welding engineering properties of two brands of electrodes *TMU-21U* and *TsU-5*, manufactured at different plants: *"Sudislavsky Welding Materials Plant", LLC*, *ESAB LLC* "*ESAB-SVEL*", and *CJSC "Elektrodnyi zavod"*.

It is established that the welding engineering properties of the electrodes: *TMU-21U* (manufacturer: *"Sudislavsky Welding Materials Plant", LLC*), *TsU-5* (manufacturer: *CJSC "Elektrodnyi zavod"*) are outside the tolerance for such a parameter as the formation of a "fingernail".

It is established that the chemical composition of the weld overlaid metal is not stable for all brands of electrodes under study and depends on the manufacturer.

It is established that the mechanical properties of the weld overlaid metal are unstable in terms of such indicators as the values of tensile strength and yield strength, and relative contraction does not meet regulatory requirements. Impact strength values are at the minimum permissible limit of values according to regulatory documents.

It is established that when calcining the electrodes, the content of diffusion hydrogen in the weld overlaid metal is reduced by almost 2.5 times, which is also recommended to be done according to *RD 153-34.1-003-01*(*RTM-1S*) clause 3.10 [1].

When comparing the content of diffusion hydrogen in electrodes manufactured at different plants, the metal weld overlaid with electrodes manufactured at the *CJSC "Elektrodnyi zavod"*, located in St. Petersburg, has the lowest hydrogen content. And the highest hydrogen content is observed when surfacing with electrodes from *ESAB LLC* "*ESAB-SVEL*" located in St. Petersburg. A lower percentage of hydrogen leads to improved welding characteristics and a reduced risk of weld defects.

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Conflicts of Interest

The authors declare no conflict of interest.