in area, it can be classed with the top group of quality, i.e. Z 35.

2. Values of KCV_{-40} of the base and HAZ metals obtained from the results of standard tests of the specimens cut out from the welded joints on steel 06GB across the weld axis and in Z direction are almost identical, this evidencing their high resistance to lamellar-brittle fracture.

3. Welded joints on steel 06GB made by manual arc welding using electrodes OK 53.70 and preheating to 70 °C are characterised by high resistance to cold cracking.

4. Rigidity of restraining and high-temperature tempering have no substantial effect on cold resistance of the weld metal and overheated region of the HAZ metal of the welded joints on steel 06GB made by using electrodes OK 53.70. At a test temperature of −40 °C their impact toughness is several times higher than the requirements imposed on the rolled metal of welded tanks intended for storage of oil and oil products. The test results obtained allow a conclusion that the requirement to perform heat treatment of individual welded joints can be revised as the sufficient experience is accumulated in operation of the tanks using the said steels.

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IMPROVEMENT OF THE TECHNOLOGY FOR SUBMERGED-ARC WELDING OF COPPER TO STEEL

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The paper gives results of investigations of the effect of some techniques on iron content of the weld metal in copper to steel joints made by submerged-arc welding. A new method was developed for welding of copper to steel by using a split electrode consisting of different-diameter wires. The method allows controlling heat input into the copper and steel edges, simplifies the process of tracking the weld line by electrode, and provides the required quality of the welds.

Keywords: *submerged-arc welding, split electrode, two wires, dissimilar joints copper + steel, edge preparation, welding parameters, electrode displacement, mechanical properties of joints*

Wide application of copper as structural material at enterprises of metallurgical and electrotechnical industries involves a difficulty in providing high performance of the welded joints on copper parts operating under conditions of high temperatures, pressures, aggressive environments, etc. In particular, this concerns the welded joints between copper and steel, as these metals are characterised by different values of thermal conductivity, melting temperature and linear and volumetric expansion factors [1]. In this connection, it is a topical task to improve the technological processes used to join these metals.

As shown by analysis of literature data, submerged-arc welding is most promising for making of copper to steel joints 5–40 mm thick. This method is characterised by high productivity and high efficiency of the arc, and often allows welding of metals of medium and large thicknesses in one pass without preheating [2, 3]. Moreover, this process provides a high level of quality and consistency of properties of the welded joints, and features improved sanitary-hygienic working conditions. At the same time, one of the drawbacks of submerged-arc welding is that it is impossible to visually observe the weld metal solidification process.

When making the copper to steel joints under conditions of arc welding the steel edge is subjected to a direct effect by the arc. Penetration of the steel edge should be minimal to limit the iron content of the weld metal, provide the required ductility of the joints and minimise the sensitivity of the weld metal to solidification cracking [4, 5].

Investigations of physical-mechanical properties of the copper to low-carbon steel welded joints operating at high values of variable temperatures [6, 7] showed that at an iron content of up to 2 wt.% the weld metal has strength equal to that of the base metal (copper) over the entire temperature range. The iron content of more than 7 wt.% in copper causes a dramatic decrease in ductile properties of the joints, which may lead to hot cracking. Comprehensive evaluation of mechanical properties, long-time strength, thermal-fatigue life, amount of accumulation of alternating plastic strains to fracture and character of fractures showed that in operation of the copper to low-carbon steel welded joints under conditions of elevated and variable temperatures the optimal iron content of the weld metal is 3–6 wt.%.

The purpose of this study was to improve the technology for submerged-arc welding of copper to steel to produce the weld metal of the welded joints free from defects in the form of pores, lacks of penetration, cracks, slag inclusions, lacks of fusion with the base metal and undercuts, provide the optimal iron content of the weld metal (from 3 to 6 %), and simplify the process of tracking the weld line by electrode.

Series of experiments were carried out to optimise the technology for welding of copper to steel with different thicknesses of the weld edges. In these experiments the angle between the steel and copper edges was varied from 0 to 45°, the welding wire diameters were varied from 2 to 4 mm, and length of displacement of the electrode towards copper was varied by 0.2 to 1.2 of thickness of the base metal. In welding of the copper to steel specimens (5+5), (10+10) and (20+20) mm thick the welding parameters were varied depending on the thickness within the following ranges: welding current — 300–450, 500–700 and 1000–1300 A, arc voltage — 32–38, 34–40 and 40–46 V, and welding speed — 18–20, 16–18 and 8–10 m/h.

Welding was performed by using wire of the MNZhKT5-1-0.2-0.2 grade and flux of the AN-60 grade by the submerged-arc method. Prior to welding the wire was subjected to mechanical cleaning, and the flux was baked at a temperature of 400–450 °C for 2 h. Surfaces of the specimens of copper M1 (0.01 % O) and steel St3 were cleaned by cleaning wheels to prevent ingress of dirt or oxides to the welding zone. The method of additional gas shielding under a flux layer was used to increase resistance of the welded joint to porosity [8].

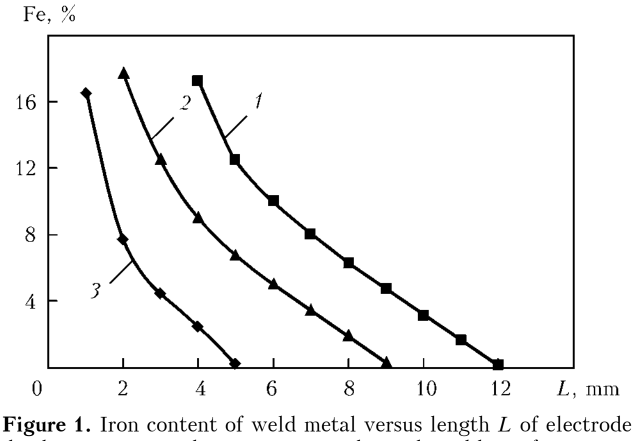

Figure 1. Iron content of weld metal versus length *L* of electrode displacement towards copper in one-electrode welding of copper to steel at different thicknesses of weld edges: *1* — (5+5); *2* — (10+10); *3* — (20+20) mm

The ABS welding head located over a movable table and VSZh-1600 power supply were employed for welding. The process was carried out at a current of reverse polarity and constant characteristic of the power supply.

Stability of the process was fixed during welding, and detachability of the slag crust and formation of the welds — after welding. Lacks of penetration, lacks of fusion, slag inclusions, cracks, pores and other defects were detected by visual examination of the welds. Then chips were taken from the upper part of the welds to determine the content of iron in the weld metal by the «wet» chemistry method. The investigations showed that the welding process was stable in all the cases, and detachability of the slag crust and formation of the welds were good. No pores or other defects were detected in the weld metal.

Optimal welding parameters and diameters of the wires providing complete penetration of the weld edges, good weld formation and detachability of the slag crust were selected depending on the thicknesses welded.

It was established that for all thicknesses the optimal preparation of the steel edge is at an angle of 30°. The copper edge can be remained non-grooved. In welding of the 20 mm thick joints the angle of the copper edge equal to 30° permits improvement of formation of the welds, although this leads to some increase in their iron content. Preparation of the steel edge at an angle of 45° leads to formation of the lacks of fusion on the side of steel, especially on the 5 and 10 mm thicknesses welded. In welding of the 20 mm thick specimens this edge preparation can be used when the copper edge remains non-grooved. However, this may cause decrease in the iron content of the weld metal to less than 3 %.

In further experiments the steel edge was prepared at an angle of 30°, and no groove was made on the copper edge for all the thicknesses welded.

The investigations showed (Figure 1) that the iron content of the weld metal within the recommended 3–6 % ranges for thicknesses of 5 mm was provided at displacement of the electrode from the weld line to 2–3 mm towards copper, for thicknesses of 10 mm — to 5–7 mm, and for thicknesses of 20 mm — to 8–10 mm.

Displacement of the electrode towards copper to a length less than the above ones leads to a dramatic increase in the iron content of the weld metal and

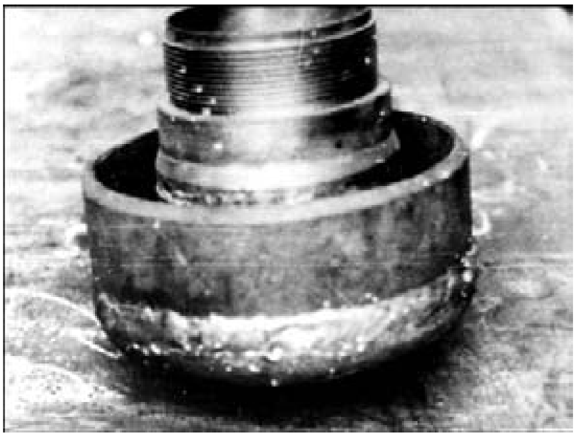

Figure 2. Appearance of a lance after welding of copper snout to steel ring

probable lacks of fusion with the copper edge, which may be related to transfer of the arc to the steel edge.

When the electrode is displaced towards copper to a length above the said ranges, incipient melting of the steel edge takes place only due to the heat of the molten metal pool, while this causes decrease in the iron content of the weld metal and formation of joints of the type of the brazed ones at the weld-steel fusion line. Also, it may cause lacks of fusion on the side of steel.

It was noted that defects in the form of lacks of fusion on the side of the steel edge or incomplete penetration of the copper edge may form at the beginning of welding of copper to steel with the 20 mm thick edges. At the end of welding the weld may displace towards steel, this causing a dramatic growth of its iron content and formation of transverse cracks. At the initial moment of welding the temperature of the copper plate has low values, which leads both to decrease in the depth of penetration of the copper edge and decrease in mobility of the arc, thus causing narrowing of the welds. Therefore, lacks of penetration or lacks of fusion on the side of the steel edge may form before achievement of equilibrium between heat input and heat removal to the copper plate.

At the end of welding the edge effect causes increase in temperature of the weld edges as the weld

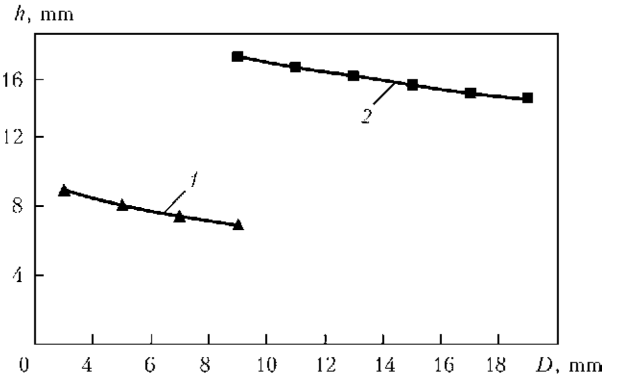

Figure 3. Effect of distance D between wires on edge penetration depth h in split-electrode welding of copper to steel with different thicknesses of weld edges. Here and in Figures 4–6: *1* — (10+10); *2* — (20+20) mm

pool approaches the end of the plates, which promotes increase in mobility of the arc and widening of the molten metal pool. As a result, more intensive melting of the steel edge leads to increase in the iron content of the weld metal. Particularly dangerous are the cases when the arc transfers to the steel edge. In such cases the weld displaces towards steel, and dramatic growth of its iron content may lead to formation of transverse cracks.

No such defects are usually detected in welding of specimens with the 5 and 10 mm thick edges. For welded joints with the 20 mm thick edges the dangerous zone at the beginning and end of welding may amount to several centimetres.

Also, such defects may form in the welded joints in transfer of the arc to the steel edge because of accidental deviations of the welding wire from its feed axis, or in beating of the welding head during movement. This is dangerous because the arc, once caught on the steel edge, continues burning with inclination to steel even after restoration of all welding parameters. Often this happens in welding of copper to steel with the 20 mm thick edges, which makes it impossible to produce sound joints when the process is performed using one electrode.

The selected conditions for welding of copper to steel with the 5 and 10 mm thick edges, edge preparation and other process parameters were recommended for welding of lances at the Frunze Metallurgical Works in Konstantinovsk. Industrial testing of this technology showed good results.

Application of the submerged-arc welding method for welding of a steel ring manufactured by refining of molten metal during melting [9] to a cast copper snout of a lance (Figure 2) allowed replacement of manual TIG welding in argon atmosphere, avoidance of the necessity to use preheating of a workpiece, simplification of the welding process and improvement of quality of the joints.

As in welding of copper to steel using one electrode even insignificant deviations of the latter from the weld axis may lead to deterioration of quality of the welded joints, while under industrial conditions it is very difficult to maintain the minimal deviation within the specified limits, it was of interest to develop such techniques that would assure the sound welded joints over wider ranges of probable deviations of the electrode from the weld axis. Also, these techniques should allow elimination of rejects at the beginning and end of welding. One of such techniques can be welding using a split electrode that sets the required width of the welds and decreases the current at the arc burning on the side of the steel edge, which, in our opinion, should have a positive effect on the quality of the welded joints. Fused-agglomerated flux was used to prevent porosity in split-electrode welding of copper to steel [10].

Series of experiments were carried out to study the possibility of using the split electrode for welding of

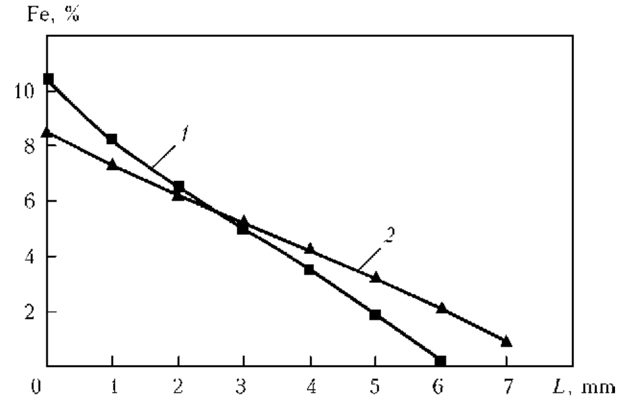

Figure 4. Iron content of weld metal versus length L of electrode displacement towards copper in split-electrode welding of copper to steel at different thicknesses of weld edges

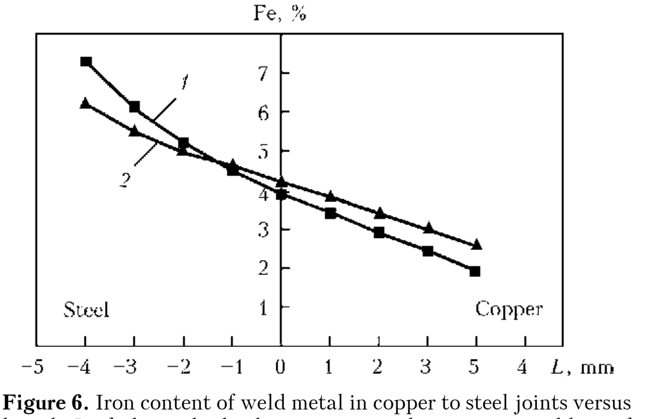

Figure 6. Iron content of weld metal in copper to steel joints versus length L of electrode displacement towards copper in welding of copper to steel by using split electrode consisting of different-diameter wires

copper to steel with the 10 and 20 mm thick edges. The effect of distance between the electrodes, welding parameters, edge preparation and displacement of the electrodes from the weld line on the quality of the welded joints was investigated during the experiments.

As proved by the investigation results on the effect of distance between the wires in the split electrode on the depth of penetration of the copper edge (Figure 3), the use of the split electrode and increase in distance between the wires in it lead to decrease in the depth of penetration of the weld edges. It was noted that two separate pools are formed in the welded joints with the 20 mm thick edges at a distance between the wires in the split electrode equal to 18 mm or more. So, the optimal distances between the wires in the split electrode were selected to be equal to 0.5–0.7 of thickness of the weld edges.

As the depth of penetration of the weld edges at the said distance between the wires was approximately 20 % less than in welding with one electrode under the same process conditions, it was necessary to accordingly increase the welding current at the split electrode.

As follows from Figures 1 and 4, the split-electrode welding technology widens the ranges of probable deviations from the weld axis, compared to one-electrode welding. However, the necessity to increase the

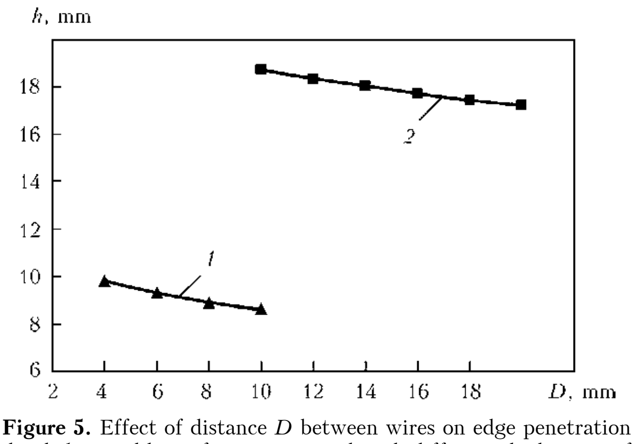

Figure 5. Effect of distance D between wires on edge penetration depth h in welding of copper to steel with different thicknesses of weld edges by using split electrode consisting of different-diameter wires

current by 20 % or more, to set the electrode displacement to a specified distance from the weld line and keep strictly to this distance during welding does not allow recommending this method for further laboratory and industrial tests.

Based on the results obtained with welding using the split electrode consisting of wires of the same diameters, it was suggested using the split electrode consisting of the different-diameter wires for welding of copper to steel, owing to which it is possible to control heat input into the copper and steel edges.

As seen from Figures 3 and 5, the use of welding with the split electrode consisting of the different-diameter wires (wire diameter on the side of steel is 30–40 % of wire diameter on the side of copper) made it possible to increase the depth of penetration of the weld edges, compared to welding with the split electrode consisting of wires of the same diameters. Welding parameters in both cases were identical.

The trend to formation of two separate molten metal pools was noted in welding with the split electrode consisting of the different-diameter wires at a distance between them equal to more than 18 mm. The optimal distances between the wires in the split electrode are 0.5–0.8 of thickness of the weld edges. In this case it is indicated to increase the welding current by about 10 % compared to welding with one electrode.

Series of experiments on welding of copper to steel with the 10 and 20 mm thick edges were carried out to study the effect of electrode displacement from the weld line on the iron content of the weld metal. Dis-

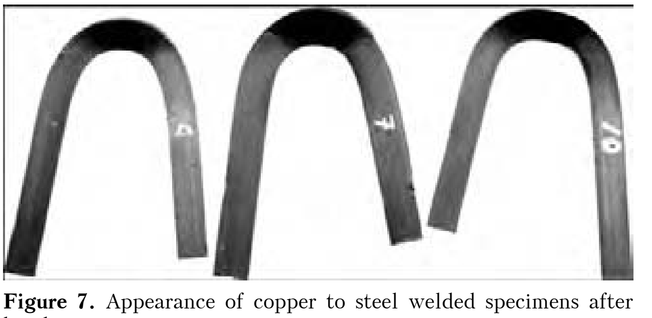

Figure 7. Appearance of copper to steel welded specimens after bend tests

placement of the split electrode consisting of the different-diameter wires was varied from 0 to 4 mm from the weld line towards copper and towards steel. The steel edge was grooved at an angle of 30°, and the copper edge remained intact.

As follows from Figure 6, the use of the split electrode consisting of the different-diameter wires made it possible to substantially increase the ranges of probable deviations of electrodes from the weld line and, at the same time, assure the high quality of the welded joints.

Based on the results obtained, it was established that a smaller-diameter wire should be set along the weld line and the specified splitting would automatically define the length of displacement of a bigger-diameter wire towards copper. This will substantially simplify the operation of preparation prior to welding and eliminate any possible mistake of an operator. Moreover, an accidental deviation of the electrode from the weld line will have no considerable effect on the quality of the welds.

Keeping to these recommendations will make it possible to produce sound welds with an iron content of 3 to 6 %, thus providing a high level of their mechanical properties at room and elevated temperatures, and allowing avoidance of defects at the beginning and end of welding. Specimens of such joints in tensile tests fracture in the base metal (copper) at σ_t = 200–210 MPa and withstand the bend angle of 180° (Figure 7). The improved technology for welding with the split electrode consisting of the different-diameter wires was tested for welding of copper to steel with the 20 mm thick edges to make solid plates of continuous casting moulds, and can be recommended for wide commercial application.

CONCLUSIONS

1. The optimal edge preparations, welding parameters and length of displacement of electrode from the weld line towards copper were selected, providing sound welds in one-electrode welding of copper to steel with thickness of the weld edges ranging from 5 to 10 mm.

2. It was established that defects may form at the beginning or end of the welds in one-electrode welding of copper to steel with the 20 mm thick edges, which does not guarantee production of sound welded joints.

3. Testing of welding with the split electrode consisting of two wires of the same diameters showed that in welding of copper to steel to provide the sound welds it is necessary to increase the welding current by 20 % or more, compared to one-electrode welding.

4. The suggested method for welding of copper to steel using the split electrode consisting of two wires of different diameters allows controlling heat input into the copper and steel edges and simplifies tracking the weld line by the electrode. This improved technology can be recommended for welding of copper to steel with the 10 to 20 mm thick weld edges.

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