

COLD RESISTANCE AND LAMELLAR FRACTURE RESISTANCE OF WELDED JOINTS ON STEEL 06GB-390

V.D. POZNYAKOV, A.Yu. BARVINKO, Yu.P. BARVINKO, A.G. SINEOK and A.N. YASHNIK
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The paper presents results of investigation of resistance of steel 06GB-390 to lamellar-tough and lamellar-brittle fractures, as well as of evaluation of impact toughness (KCV_{-40}) of the weld and HAZ metals of butt joints on this steel (as-welded and after heat treatment). The joints were welded in free and rigidly restrained states. It is shown that steel 06GB-390 is not susceptible to lamellar-tough and lamellar-brittle fractures, while impact toughness of the weld and HAZ metals of the butt joints hardly changes in any of the cases.

Keywords: arc welding, low-alloy steels, oil storage tanks, HAZ metal, impact toughness, heat treatment of welded joint, welding in rigid contour, welding strains, lamellar fracture

Because of fluctuations of oil prices in the world markets, the CIS and European countries are active in intensive construction of tanks with a capacity of 50,000–75,000 m³. In the majority of cases such tanks have the basic and protective walls, this excluding the need for making fire dikes around each tank. As a rule, the 24–30 mm thick rolled plates of steels with $\sigma_y \geq 345$ –440 MPa are used to manufacture the lower ring of the tank wall. The regulatory documents [1, 2] recommend steels 09G2S, 15G2ANNb, 10G2FB, 18G2AV etc. with a carbon content of 0.1–0.2 % and sulphur content of up to 0.035–0.040 % to be used to manufacture the lower rings of walls of high-capacity tanks. The long-term experience in construction and operation of different-capacity tanks made by using the above steels shows that reliability and performance of metal structures is at a high level, provided that requirements of these regulatory documents are kept to.

At the same time, new high-strength low-alloy steels of the 06GB (strength class 390) and 06G2B (strength class 440) grades have been intensively applied in the last years in Ukraine for fabrication of welded metal building structures. A distinctive feature of these steels is their low (almost 2 and 7 times lower than indicated in specifications [1, 2]) concentration of carbon and sulphur (Table 1), which should ensure their low sensitivity to cold cracking and, at the same time, high impact toughness at negative temperatures. This is confirmed by the data of study [3], which are indicative of the fact that steels 06GB and 06G2B in

the quenched + tempered state at thickness of the rolled plates equal to 8–50 mm have a uniform structure across the plate section (Figure 1), high mechanical properties and high cold resistance (Table 2), and are characterised by good weldability [4]. Also, according to all indicators these steels are promising for fabrication of high-capacity tanks.

However, in selection of steels for fabrication of tanks it is necessary to take into account peculiarities of operation of individual structural wall and bottom elements. It is a known fact that, unlike the vertical and horizontal welds of the walls, the circumferential one-sided welds connecting branch pipes to the wall are made under the rigid contour conditions as well (Figure 2, section 1–1). At wall thicknesses $t \geq 25$ mm, the volume of the deposited metal is sufficiently big, this causing substantial transverse shrinkage and for-

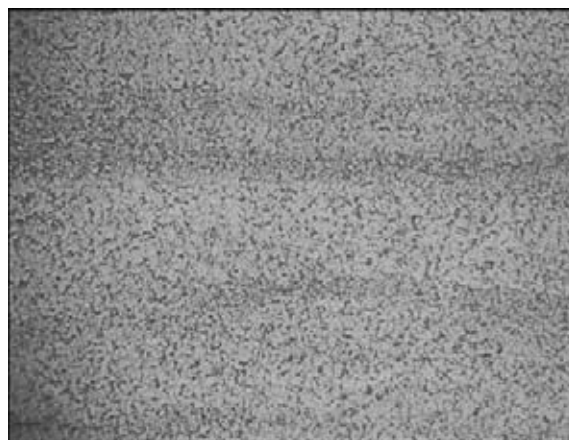


Figure 1. Microstructure ($\times 100$) of 26 mm thick rolled metal of steel 06GB

Table 1. Chemical composition of steels 06GB and 06G2B, wt. %

Steel grade	t , mm	C	Mn	Si	V	Nb	S	P	C_{eq}
06GB	26	0.06	1.27	0.20	0.037	0.014	0.004	0.007	0.29
06GB	30	0.07	1.27	0.27	0.036	0.013	0.005	0.006	0.31
06G2B	30	0.07	1.42	0.20	0.057	0.038	0.007	0.008	0.34

Table 2. Mechanical properties of steels 06GB (class 390) and 06G2B (class 440)

Steel grade	t , mm	σ_y , MPa	σ_t , MPa	δ_5 , %	ψ , %	KCV_{-40} , J/cm ²	σ_y/σ_t
06GB	26	393	498	32.0	80.6	265	0.79
06GB	30	391	477	34.4	79.7	364	0.82
06G2B	30	467	554	33.5	80.4	303	0.84

mation of high residual stresses. Apparently, this may lead to formation of cold cracks in the weld metal. In addition, as the circumferential welds are inspected by the visual-optical method or by the dye penetrant method, this does not exclude the presence of sharp stress raisers in the welded joints, which may lead to decrease in their resistance to brittle and tough fractures. The probability of brittle fracture in the presence of high residual stresses and at low temperatures is evidenced by the data of study [5]. Study [6] also shows that increase in the level of residual stresses and formation of heterogeneous structure in the welded joint lead to a 20–25 % decrease in impact toughness. Moreover, as follows from studies [7, 8], plastic deformation plays a decisive role in probable initiation of not only the brittle fracture but also the tough one.

The stressed state of the welded joints between the strengthening cover plate and wall (Figure 2, section 2–2) and in the assembly of welding of the thickened bottom edge of bottom box to the wall (Figure 3) is a bit different. Welding strains here act in a direction of the wall thickness and bottom, this initiating their lamellar cracking.

Formation of lamination is characteristic of the rolled plates at $t \geq 20$ mm. The key factor affecting formation of lamellar fractures is the presence of sul-

phide or oxide inclusions. They are extended in the process of rolling of the plates to form a stringer or laminated structure [9, 10]. Study [10] shows that the quality of steel in Z direction is well described by standard characteristics of ductility ψ_Z and impact toughness KCV . To eliminate lamination in welded structures the authors of study [11] recommend decreasing the sulphur content of steel to $S \leq 0.01$ %, and in study [9] it is suggested that steels with $S \leq 0.007$ % and $\psi_Z \geq 25$ % should be classed with those having high resistance, and steels with $S > 0.020$ % and $\psi_Z \leq 8$ % – with those having low resistance to lamellar cracking.

In this connection, it is necessary to evaluate resistance of rolled plates of steels of the 06GB and 06G2B types to formation of lamellar cracks, and resistance of welded joints to lamellar-brittle fracture, as well as check whether their cold resistance will change in welding in a rigid contour. So, investigations in this area became the purpose of this study.

Steel 06GB 20, 26 and 30 mm thick, and butt joints on this steel 26 mm thick were chosen as investigation objects.

Resistance of the steels to lamellar fracture was evaluated according to GOST 28870–90 by the results of tests of three specimens cut out from the welded joints made by manual arc welding using electrodes

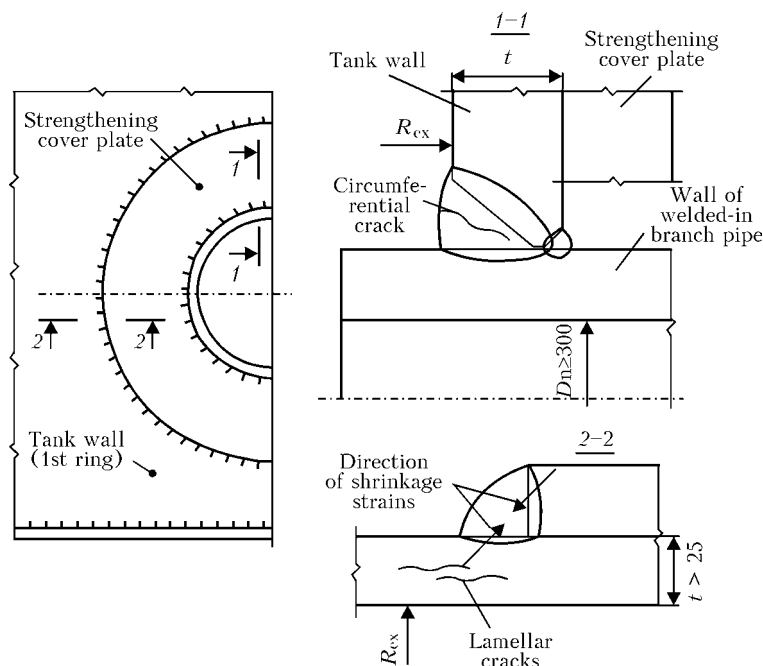


Figure 2. Schematic of the assembly of welding of branch pipe into the lower wall ring by indicating location of probable formation of lamellar cracks

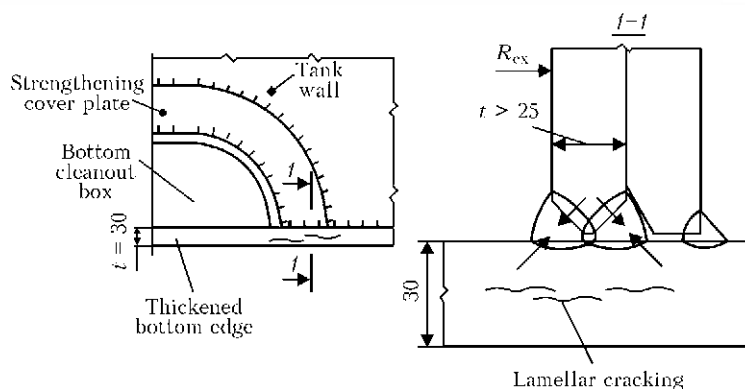


Figure 3. Schematic of formation of lamellar cracks in locations of joints between the wall and thickened edge of bottom cleanout box

Table 3. Results of tensile tests of 06GB steel specimen in Z direction

t , mm	σ_y , MPa	σ_t , MPa	δ_5 , %	ψ , %
20	<u>428; 437; 444</u> 436	<u>510; 513; 510</u> 511	<u>45.1; 45.9; 44.4</u> 45.0	<u>81.1; 78.8; 81.2</u> 79.6
26	<u>388; 388; 385</u> 387,2	<u>506; 506; 500</u> 504	<u>46.6; 48.1; 48.9</u> 47.9	<u>81.2; 81.1; 81.2</u> 81.1
30	<u>380; 358; 373</u> 370	<u>489; 482; 484</u> 485	<u>35.3; 36.8; 37.6</u> 36.6	<u>71.6; 69.7; 67.9</u> 69.7

OK 53.70. Structural elements of the billets welded and shape of cross sections of the welded joints and welds met requirements imposed on the joints of the T8 type according to GOST 5264–80. Initial and end regions of the welded joints not less than 30 mm long were removed. Specimens for tests according to GOST 1497–84 were made from the remaining part of the welded joints. The scheme of cutting out of specimens is shown in Figure 4. The specimens were tested at +20 °C. The values of σ_y , σ_t , δ_5 and ψ_Z were determined during the tests. The test results are shown in Table 3.

Comparative evaluation of mechanical properties of steel 06GB, 26 and 30 mm thick, along (see Table 2) and across the rolled plate shows that this steel has no anisotropy of properties. By the value of reduction in area ψ_Z this steel can be classed with the top group of resistance to lamellar fractures, i.e. Z 35.

Resistance of welded joints on steel 06GB, 26 and 30 mm thick, to lamellar-brittle cracks was evaluated from the results of impact bend tests of the specimens (type IX according to GOST 9454–78) made from the cruciform welded joints, similar to those used for evaluation of resistance of the steel to lamellar fracture. The specimens from the 30 mm thick welded joints were made only in the as-welded state, while those from the 26 mm thick joints – also after their heat treatment (tempering at 620 °C for 2 h). The scheme of cutting out of specimens is shown in Figure 5. Notches on the specimens were made along the fusion line (FL), in the HAZ metal at a distance of 2 mm from FL, and in the base metal at a distance of 8 mm from FL. The specimens were tested at –40 °C.

Results of the impact bend tests of the specimens (Table 4) are indicative of the fact that tempering has

no significant effect on impact toughness of both base metal and FL and HAZ regions of the welded joints. Cold resistance of HAZ metal of the welded joints on steel 06GB is at a level of the base metal ($KCV_{-40} \geq 220 \text{ J/cm}^2$), and is much in excess of the requirements given in specifications for the steel ($KV_{-40} \geq 98 \text{ J}$, which corresponds to $KCV_{-40} \geq 123 \text{ J/cm}^2$) [12]. Decrease in impact toughness, compared to the base metal, in FL of the welded joints was observed in all the cases. KCV_{-40} of the 26 mm thick joints on this steel in the as-welded state ranged from 42 to 305 J/cm^2 (the average value being 130.8 J/cm^2 by the results of testing seven specimens), while after high-temperature tempering it varied from 87 to

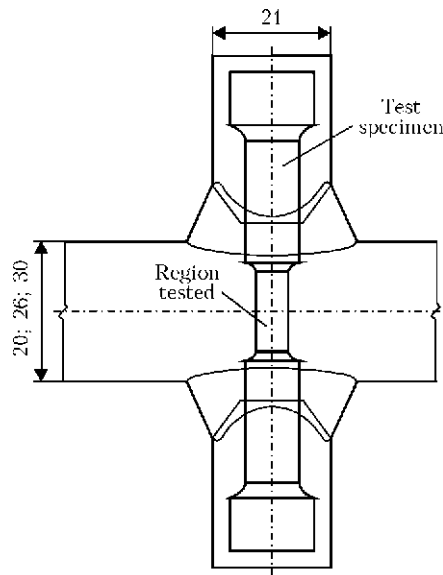


Figure 4. Scheme of cutting out of specimens from the welded joints made in accordance with GOST 28870–90

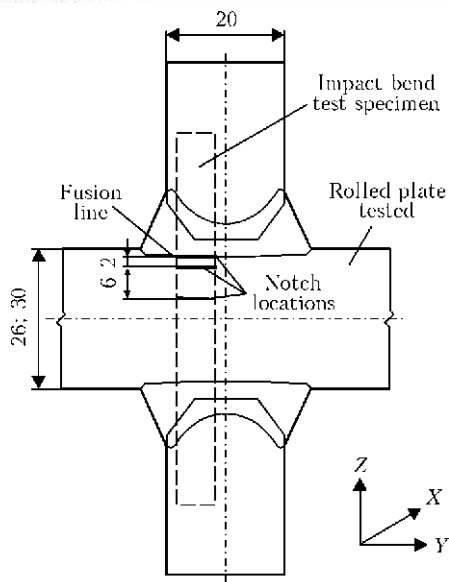


Figure 5. Scheme of cutting out of specimens from cruciform welded joints with indication of locations of notches

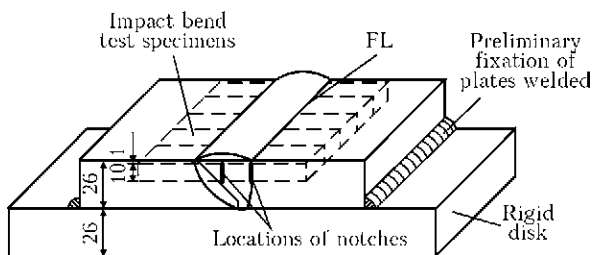


Figure 6. Scheme of cutting out of specimens from butt joints made in rigid contour with indication of locations of notches

197 J/cm² (the average value being 128 J/cm² by the results of testing three specimens). The almost 35 % lower values of impact toughness, compared to the base metal, were obtained in testing of the specimens with a notch made along FL, which were cut out from the 30 mm thick welded joints. This decrease can be explained by violation of homogeneity of chemical composition and structure of metal in the given region of a welded joint. At the same time, it should be noted that even in the as-welded state the values of impact toughness of the butt joints on steel 06GB were much higher than the level of the requirements imposed on the rolled plates recommended for fabrication of high-capacity tanks [2].

Special investigations were carried out to experimentally check the effect on cold crack resistance and impact toughness of the weld and HAZ metals of the welded joints by the rigidity of their restraining. Four butt joints (S8 according to GOST 5264–80) were made from the 26 mm thick plates by the developed welding technology using 4 mm diameter electrodes OK 53.70 and preheating to a temperature of 70 °C. Two of them were welded in the unrestrained state (joints 1 and 2), and another two (joints 3 and 4) – in the rigidly restrained state (Figure 6). As evidenced by the data of study [13], the value of residual stresses in the HAZ metal of such joints varies from 0.5 to 1.0 of yield stress of the base metal.

Table 4. Results of impact bend tests of specimens made from welded joints on steel 06GB in Z direction

t, mm	Notch location	KCV ₋₄₀ , J/cm ²	
		As-welded	After heat treatment
26	FL	163; 253; 305; 98; 77; 42	87; 197; 101
	In HAZ metal (FL + 2 mm)	332; 294; 325; 345; 346; 347	348; 348; 347
	In base metal (FL + 8 mm)	321; 333; 328	347; 345; 345
30	FL	181; 281; 240; 85	–
	In HAZ metal (FL + 2 mm)	334; 335; 326; 223	–

Table 5. Results of impact bend tests of specimens made from 26 mm thick butt joints on steel 06GB

Welding condition	Heat treatment	KCV ₋₄₀ , J/cm ²	
		FL	Weld metal axis
In unrestrained state	No	342; 371; 338 350	282; 246; 209 246
	Tempering	339; 340; 341 340	290; 240; 220 250
In rigidly restrained state	No	339; 342; 340 340	244; 251; 200 232
	Tempering	248; 341; 343 311	246; 246; 172 221

After welding, joints 2 and 4 were subjected to high-temperature tempering at 620 °C for 2 h. Then macrosections were made from all the welded joints to check the presence/absence of cold cracks in the welded joints, and specimens (type IX according to GOST 9454–78) were prepared for impact bend tests. Some specimens had notches in FL, and some – in the weld metal. Results of the impact bend tests of the specimens carried out at –40 °C are given in Table 5.

As indicated by analysis of the macrosections, all the welded joints were free from cracks, this evidencing high resistance of the welded joints on steel 06GB made by the above technology to cold cracking. Independently of the rigidity of restraining, impact toughness of the weld metal and overheated region of the HAZ metal of the said welded joints was several times higher than the requirements imposed on the rolled plates used to fabricate tanks for oil and oil products both in the as-welded state and after high-temperature tempering [14]. High-temperature tempering has no substantial effect on cold resistance of the welded joints on steel 06GB.

CONCLUSIONS

1. 20, 26 and 30 mm thick rolled metal of steel 06GB has high resistance to lamellar fracture. In reduction

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

V.N. KOLEDA

E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

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