DEVELOPMENT OF SURFACE CRACK-LIKE DEFECT IN WELDED JOINTS OF 06GB-390 STEEL AT CYCLIC LOADING

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The paper presents the results of experimental studies of a surface crack-like defect in a butt welded joint on flat specimens of 06GB-390 steel under cyclic loading to formation of a through-thickness crack. Dependence of growth of a surface crack-like defect in vertical butt welded joints on the loading cycle number was established for design rings of walls of oil storage tanks. It is shown that in the presence of surface defects in welded joints application of rolled plates of 06GB-390 steel for the design rings of tank wall provides a substantial improvement of their operational safety.

Keywords: *arc welding, butt welded joints, surface crack-like defect, cyclic loading, fatigue crack initiation, crack propagation, tank wall thickness*

Operation of oil storage tanks with single or double walls (main and shielding) envisages everyday visual inspection of their surfaces with statement of the fact of the presence or absence in them of visually detectable surface cracks or oil spots from oil sipping through through-thickness cracks. Appearance of oil traces on the wall surface is the result of the final stage of development of a surface or inner crack-like defect. Surface crack after growing and reaching the opposite surface of tank wall is the most critical defect. Therefore, determination of the number of cycles of tank draining-filling with oil with its accepted operation mode that leads to formation of a through-thickness crack is an urgent task both for regular single-wall and for double-wall tanks. Determined cyclic fatigue life of welded joints of tank walls with the considered surface defects, allows precising their repair time and preventing further development of the through-thickness crack. Investigation of cyclic fatigue life of surface crack growing, including its reaching the opposite surface, is the first stage. It is necessitated by application over the recent years of new steels of grades S440, S390 and S350 for tanks of V = 50–75 thou m^3 capacity [1]. These steels differ from those recommended by normative document [2, 3] by a low content of carbon and sulphur, as well as mechanical properties (ductility, cold resistance, KCV), greatly exceeding the current requirements [2, 3].

It should be noted that steels of grade S390 of 10–30 mm thickness with required impact toughness $KCV \geq 50$ J/cm^2 at temperature T = −20–40 °C are practically absent in normative documents [2, 3] among those recommended for tank walls. This niche is occupied by new generation steels 06GB-390 and 09G2SYuch-U [1, 4] (steel grade will be omitted further on in designation of 06GB-390 steel). Rolled plates from 06GB steel have been successfully tried out in construction of four tanks of V = 50 thou m^3 capacity in LPDS «Mozyr» (Belarus Republic). Steel of 8–50 mm thickness has $KCV > 118$ J/cm^2 at T = = +20 − −40 °C [1]. T = −40 °C is the minimum design temperature for all the CIS and European countries. As the results of testing specimens at T = +20 and −40 °C are in the upper region of the curve of KCV dependence on testing temperature, data obtained at T = +20 °C are extended to the entire upper plateau of this curve.

Figure 1 shows the schematic and dimensions of tested specimen of welded joints with a crack-like notch. PWI technology of welding rolled plates from 06GB steel ensures equivalent strength of the welded joint [5]. Transverse butt weld had through-thickness penetration. Mechanical properties of rolled plates of 06GB steel obtained on three specimens are as follows: thickness δ = 20 mm; yield point σ_y = 387.4 MPa/mm^2; ultimate tensile strength σ_t = 477.9 MPa/mm^2; relative elongation δ_5 = 35.6 %; relative reduction ψ_z = 79.6 %; impact toughness KCV_{-40} = = 232 J/cm^2; σ_y/σ_t = 0.81.

At welded joint testing for static bending fractures ran though the base metal. Along the fusion line KCV_{-40} of welded joint metal was equal to 341.1 J/cm^2 (average from three specimens).

Notch in welded joints was milled along the fusion line with rounding-off radius r = 0.25 mm, its depth being 6 mm, and length — 39 mm (see Figure 1). All together nine specimens were tested, seven of them from 06GB steel. Three of them were pre-stretched before testing to obtain residual deformation δ_{res} = = 0.8–1.0 %. For comparison two specimens were made from 09G2S-12 steel with 0.01 wt.% S and 0.013 wt.% P content.

Specimens were tested at harmonic cyclic loading P_{cyc} in TsDM-200pu pulsator with 5 Hz frequency. Maximum cycle stress was equal to $\sigma_{max} = 2/3\sigma_y$, that corresponds to values of maximum circumferential stresses in the tank wall, and minimum cycle stress $\sigma_{min} = 0.1\sigma_{max}$. Cross-section of specimens from 06GB

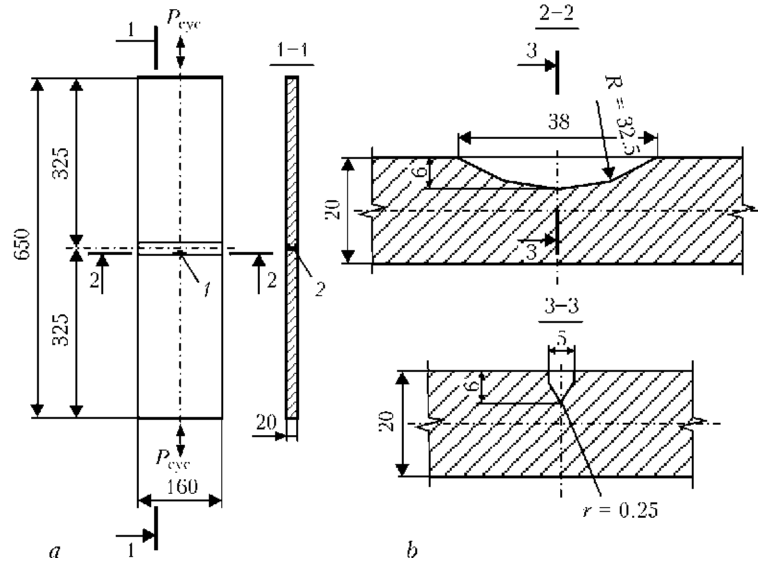

Figure 1. Schematic (*a*) and dimensions (*b*) of specimen of 06GB steel welded joints for cyclic crack resistance testing: *1* — notch along the fusion line in HAZ; *2* — weld reinforcement removed from two sides

steel was taken to be 160 × 20 mm, and that from steel 09G2S-12 — 160 × 16 mm. Dimensions and maximum stresses at cyclic loading allowed performance of crack resistance testing of welded joints with development of surface crack-like notch under the conditions of a plane-strain state up to formation of a through-thickness crack on the opposite surface and its propagation up to length $l = 2a$ (30–40 mm). Taken dimensions of the initial notch were close to visually detected cracks in vertical welded joints of the wall of tanks of V = 10,000, 20,000 and 50,000 m^3 capacity. At the first stage of testing, number of loading cycles, corresponding to the moment of fatigue crack formation over the entire notch front was determined, and the sequence of the process of its development from the notch up to reaching the opposite surface was established. Schematic of formation of a through-thickness crack is given in Figure 2. Testing results are given in the Table.

On four specimens, which were tested without pretension, the average cycle number to crack initiation along the entire notch length was equal to 14.5 thou. Testing of two specimens (6, 7) at initial residual tensile deformation δ_{res} = 0.8–1.0 % showed an increase of cycle number before crack initiation over the entire notch front by almost 30 %. Such a result was obtained due to reduction of the notch sharpness at pre-stretching of specimens before their plastic deformation. Crack growing on specimen 5 can be regarded as the result of notch deviation from the fusion line or absence of a clear-cut fusion line across thickness. After formation of a fatigue crack in specimens over the entire notch front the coefficient of stress concentration in their tips became the same. Under these conditions, the number of loading cycles in specimens 1–7 before fatigue crack reaching the opposite surface (taking scatter into account) was actually the same and was equal to N = 10.3 thou on average. Cracks on the notch surface and on the opposite side have the same length in all the specimens. Process of fatigue crack formation and its growing up to reaching the opposite surface is well-illustrated by Figure 3. Fracture symmetry is disturbed by the presence of a defect

Results of testing specimens with initial surface notch along the fusion line of the HAZ of 06GB and 09G2S-12 steel welded joint

Specimen number	Steel grade	Welded joint state	Number of cycles by the moment of crack initiation over the entire notch front, thou	Initial length of crack on specimen surface, mm	Number of cycles from crack initiation over the entire notch front up to formation of through-thickness crack, thou	Crack length from the notch side at formation of through-thickness crack, mm	Length of through-thickness crack at its reaching the opposite surface, mm
1	06GB	As-welded in free state	16.9	42	13.4	59	15
2			12.6	40	10.0	56	10
3			14.2	42	12.8	56	10
4			14.2	40	10.0	57	10
5	06GB	Pre-stretching of specimen up to 0.8–1.0 % at residual deformation	9.9	40	7.9	59	10
6			20.0	40	7.2	59	10
7			18.2	41	10.9	58	11
8	09G2S-12	As-welded in free state	20.4	41	13.6	54	12
9			49.2	41	13.3	49	8

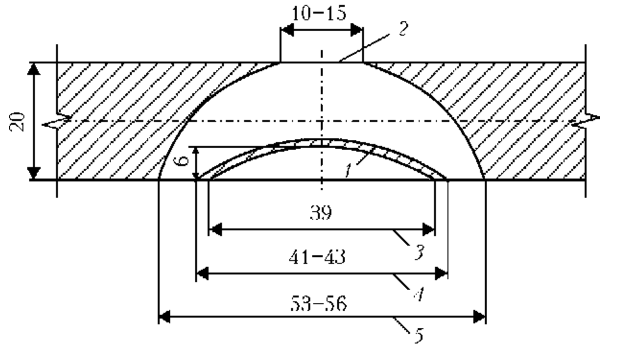

Figure 2. Schematic of formation of initial crack from the notch and its growing up to through-thickness crack with reaching opposite surface: *1* — initial through-thickness crack; *2* — initial notch; *3* — length of crack-like mechanical notch; *4* — initial crack length; *5* — crack length at its growing to through-thickness crack

in the weld (lack-of-fusion on the right side). In Figure 3 it is seen that at the beginning the fatigue crack about 5 mm deep forms over the entire notch front, and then it propagates across specimen thickness reaching its opposite surface (its initial length is equal to 10–5 mm).

Results of testing specimens from 09G2S-12 steel confirmed the known data that steels with a developed yield plateau have a high resistance to initiation and development of fatigue cracks [6, 7]. However, low cold resistance (by impact toughness value) of the above steels essentially limits their application in structures operating at low temperatures.

For practical application it is important to know the number of cycles of tank wall loading, time of fatigue crack initiation from the available surface crack-like defect (notch), and its growing across thickness up to formation of a through-thickness crack. Results of testing only specimens 1–4 having no softening of the notch sharpness were considered. Average cycle number was equal to 14.5 and 10.3 thou. For real structures assessment of results obtained on the specimens was made allowing for the safety factor per loading cycle number. Interstate Research Committee on Pressure Vessels recommends taking this coefficient to be equal to 20 [8]. Then the real number of loading cycles up to fatigue crack formation is equal to 725, and up to its growing with formation of a through-thickness crack — 515 cycles. Obtained data indicate that at application of 06GB steel for design rings of tank wall and annual number of loading cycles of 120 (operating mode of most of oil tank farms) fatigue crack initiation from a sharp surface notch 40 mm long present on the wall surface can be expected in 6 years. The process of transition of the formed fatigue crack into a through-thickness crack at tank wall thickness of 20 mm occurs during 4 years of operation. Obtained data are in good agreement with normative document [9], which specifies performance of partial examination of new tanks every 5 years (after 20 years of operation — every 4 years) and complete examination every 10 and 8 years, respectively. Such terms allow at partial examination performing visual determination of the presence of surface defect formed on the wall, and in the case of fatigue crack development from it — detecting it by

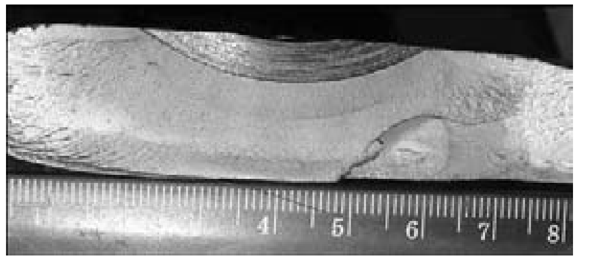

Figure 3. View of the surface of through-thickness fatigue crack (specimen 1)

ultrasonic testing at the next complete examination of the tank.

Thus, presented results give an assessment of just the process of fatigue crack initiation from surface defect and its growing across specimen thickness up to its reaching its opposite surface. Fatigue crack, however, can also initiate from inner crack-like defects (lacks-of-fusion along the edges, different flat inclusions, etc.) or surface defect, located on tank wall inner surface. In this case, the surface crack will be manifested already at the stage of through-thickness one. This part of investigations is the second stage of the work, at which the process of propagation of through-thickness fatigue crack in the initial section of fatigue development diagram [8] along the fusion line of welded joint on 06GB steel 20 mm thick will be studied for walls of oil storage tanks. Results of these investigations will be published in one of the next issues of the journal.

CONCLUSIONS

1. Butt welded joints of rolled plates of 06GB steel in the case of walls of oil storage tanks have a high resistance to development of a fatigue crack from surface sharp defects in the direction of plate thickness under cyclic loading at plane deformation.

2. Terms of partial and complete examination of tanks from 06GB steel specified in normative documents allow detecting in their wall sharp surface defects before fatigue crack initiation from them, and in the case of its initiation allow taking the required safety measures and repairing the detected defects.

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