INCREASE OF FATIGUE LIFE OF WELDED T-JOINTS WITH LACK OF ROOT PENETRATION USING HIGH-FREQUENCY MECHANICAL PEENING

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Represented are the results of fatigue tests of welded T-joints from low-alloyed steels 09G2S, 10KhSND and 15KhSND. Manufacture of such joints embedded a structural lack of root penetration of 3 × 3 mm cross section along the whole length of the welded joint. The purpose of present study is an experimental evaluation of effect of extensive lacks-of-penetration on fatigue life of the welded joints on low-alloyed steels strengthened by high-frequency mechanical peening which used in manufacture of critical welded metal structures. Testing of welded specimens was carried out with zero-to-tension stress cycle at 5 Hz frequency. It is shown that the fatigue life of high-loaded T-joints from low-alloyed steels strengthened by given technology and containing extensive structural lacks of root penetration of 3 × 3 mm cross section, is in a range of spread of experimental data for strengthened welded joints made with full penetration. Failure of the specimens at that takes place from the lack of root penetration along the rib and their fatigue life rises up to 10 times in comparison with that of unstrengthened specimens with full penetration. As was stated, the presence of structural lack-of-penetration in the unstrengthened high-loaded T-joints, cross ribs of which do not transfer main load, provides no effect on the fatigue life since formation and propagation of cracks take place on zone of weld metal to base metal transfer. 13 Ref., 4 Figures.

Keywords: *welded metal structures, low-alloyed steels, T-joint, fatigue life, high-frequency mechanical peening, fatigue*

Most of welded metal structures of engineer designation (bridges, overpasses, stationary offshore structures) are manufactured from low-alloyed steels. As a rule welded T-joints make up to 70 % in such structures. Lack of root penetration is one of the most possible defects in welding of elements of metal structures by fillet welds. It is well known fact that the lacks of penetration are the reason of appearance of significant stress concentrations and promote rapid decrease of fatigue limit of the welded joints, in particular butt ones [1–3]. Presence of lack of root penetration provides smaller effect on fatigue life of the welded T-joints, cross ribs of which do not transfer main load. The lacks-of-perpetration in such joints can show no signs of presence during the whole service life at small levels of alternating loads and fatigue failure will take place in a zone of weld transfer on base metal.

Problem of increase of bearing capacity of the welded metal structures under service with the help different repair operations applying strengthening post-weld technologies is relevant in present time. High-frequency mechanical peening (HFMP), also known in literature as an ultrasonic impact treatment [4–9], finds increasingly wide application for rise of fatigue strength of the welded joints. Using of specified method of treatment of the welded joint is widely studied as for application to the T-joints with full penetration in as-welded condition as well as after running of specific number of cycles of stress change [8, 10–12]. It was shown that strengthening using HFMP technology allows significantly increasing characteristics of the fatigue strength of such joints and levels of applied stresses, respectively. There are no data in investigations performed on fatigue strength of welded T-joints strengthened by HFMP with technological or structural lacks of root penetration, including at increased levels of applied stresses correspondent to strengthened welded joints.

The aim of the present work is evaluation of effect of lacks-of-penetration on fatigue life of the T-joints from low-alloyed steels strengthened by HFMP.

Fatigue tests were carried out on specimens of welded T-joint from low-alloyed steels 09G2S (σ_y = 375 MPa; σ_t = 510 MPa), 10KhSND (σ_y = = 420 MPa; σ_t = 610 MPa) and 15KhSND (σ_y = = 400 MPa; σ_t = 565 MPa). Billets for specimens from these steels were cut out from sheet products so that a long side was oriented along the rolled products. Cross ribs were welded from two sides by fillet welds performed by manual arc welding with UONI-13/55 grade electrodes. The lack of

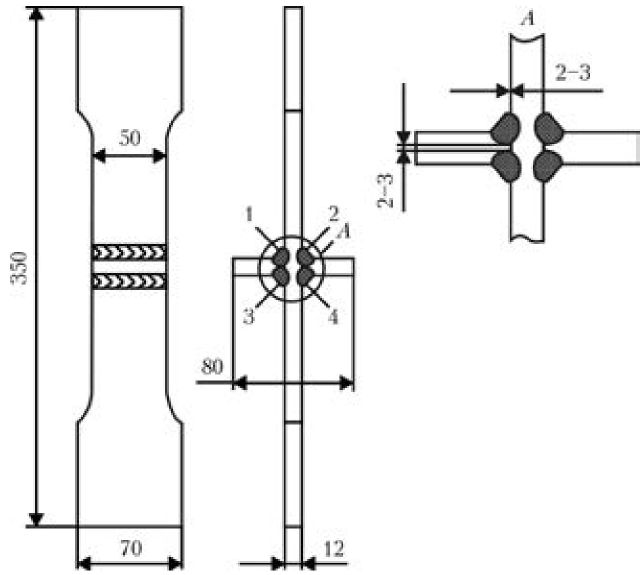

Figure 1. Shape and dimensions of specimens of T-joints from low-alloyed steels

root penetration of 3 × 3 mm cross section along the whole length of the specimen (length of weld) was formed by means of increase of gap between a plate and welded rib as well as rise of root face width. Figure 1 shows shape and geometry dimensions of the specimens with lack of root penetration. Thickness of the specimen made 12 mm that is caused by wide applicability of rolled

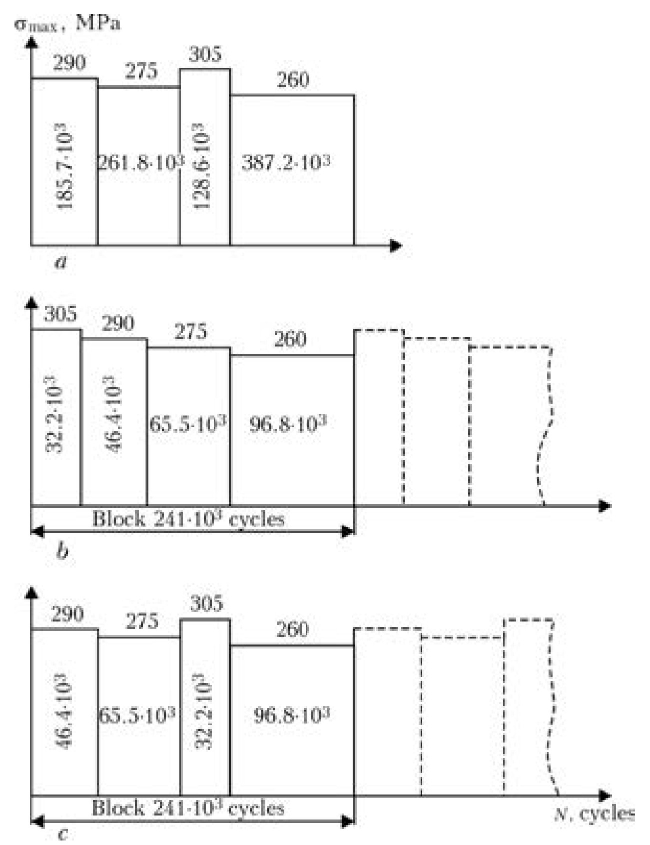

Figure 2. Schemes of loading of specimens of welded T-joints from 09G2S steel at multilevel (*a*) and block loading with descending (*b*) and quasirandom (*c*) sequences of loading application

products of this thickness in the welded structures, and width of working part of the specimen was taken based on capacity of testing equipment. Compact manual equipment US-TREAT-1.0 was used for strengthening of the welded joints. Fatigue tests of the specimen were performed on URS-20 machine at alternating zero-to-tension stress with 5 Hz frequency at regular and non-regular loadings (Figure 2). Each of the specimens was tested up to complete failure.

Two specimens from 10KhSND steel were tested at increased levels of applied stresses for determination of place of crack nucleation (along a fusion line or starting from lack-of-penetration) in T-joints with lack of root penetration. Zones of weld transfer on base metal 1 and 2 (see Figure 1) were treated by HFMP in as-welded condition. Maximum applied stress 290 MPa was used for the tests. Fatigue cracks of up to 0.5 mm depth (up to 3 mm length) appeared after running of 102.3 and 119.0 thou cycles of stress change in the unstrengthened zones (zone 4 of specimen 1 and zone 3 of specimen 2, respectively). Zones damaged by fatigue cracks were treated using HFMP and the tests were continued with the same levels of loading. Similar cracks appeared in unstrengthened zone 3 of specimen 1 and zone 4 of specimen 2 after running of 232.5 and 152.8 thou cycles of stress change, respectively, in a course of further tests. The tests were continued after HFMP of the zones damaged by fatigue cracks. Specimen 1 failed after 858.9 thou cycles, and specimen 2 — after 1823.4 thou cycles of stress change. In both cases the fatigue cracks developed from the lacks-of-penetration and failure took place along the welded ribs which do not transfer main load. Figures 3 and 4 show failed specimens.

Obtained test results indicate that no signs of the lack-of-penetration in unstrengthened T-joints, cross ribs of which do not transfer main load, can appear during the whole service life since the failure will take place along the zone of weld transfer to base metal. The life of T-joints strengthened by HFMP and made with full penetration [10] will be in a range of 600–1100 thou cycles at the level of applied maximum stress 290 MPa based on stress–cycle diagram. The failure at that takes place along the zone of weld transfer to base metal. Thus, fatigue life of the joints after strengthening by HFMP increases 5–10 times in comparison with that of the unstrengthened specimens with full penetration [10] and failure takes place from the lack-of-penetration along the rib. Also, a high efficiency of strengthening of the welded joints with fatigue cracks of insignificant depth (≈0.5 mm) using HFMP is confirmed by investigation performed.

Evaluation of effect of level of stresses applied to the place of crack nucleation (along the fusion line or from the lack-of-penetration) was carried out on specimens 3 and 4 of T-joints with lacks-of-penetration made from 09G2S and 15KhSND steels, respectively. Strengthening of all zones of welded joint using HFMP was carried out in the as-welded condition. Specimen from 09G2S steel was tested at the level of maximum applied stress 260 MPa. The failure from lack-of-penetration along the rib took place after 1127.2 thou cycles of stress change (Figure 4, *c*). The failure along the fusion line [11] in the range of 1150–1950 thou cycles of stress change occurred in the joints with full penetration which were strengthened using HFMP in the as-welded condition at loading by maximum stress cycle 260 MPa at similar tests. Specimen from 15KhSND steel was tested at level of maximum applied stress 300 MPa. The failure from lack-of-penetration along the rib took place after 830.7 thou cycles of stress change (Figure 4, *d*). The failure along the fusion line in a range of 600–900 thou cycles of stress change took place in the joints with full penetration, which were strengthened at loading by maximum stress 300 MPa at similar tests. Thus, the failure of studied specimens took place from the lack-of-penetration along the rib in the range of applied maximum stresses 260–300 MPa typical for high-cycle area of strengthened T-joints from low-alloyed steels. At that, fatigue life of the welded joints increases up to 10 times in comparison with that of the unstrengthened specimens with full penetration [11].

It is well known fact that the metal structures of engineer designation are, as a rule, exposed to complex irregular modes of loading [13] in the process of operation. Four specimens of welded T-joints with lack-of-penetration from 09G2S steel were manufactured for evaluation of effect of loading type (multilevel or block) on efficiency of strengthening using HFMP technology. Figure 2 shows the schemes of loading of specimens, indicating the levels of applied maximum stresses, their sequence and amount of cycles on each level. All the specimens were strengthened by HFMP in the as-welded condition. Similar tests of the specimens of T-joints with full penetration, which were strengthened using HFMP, were carried out earlier considering specified schemes of loading, and their results are shown in works [11, 12].

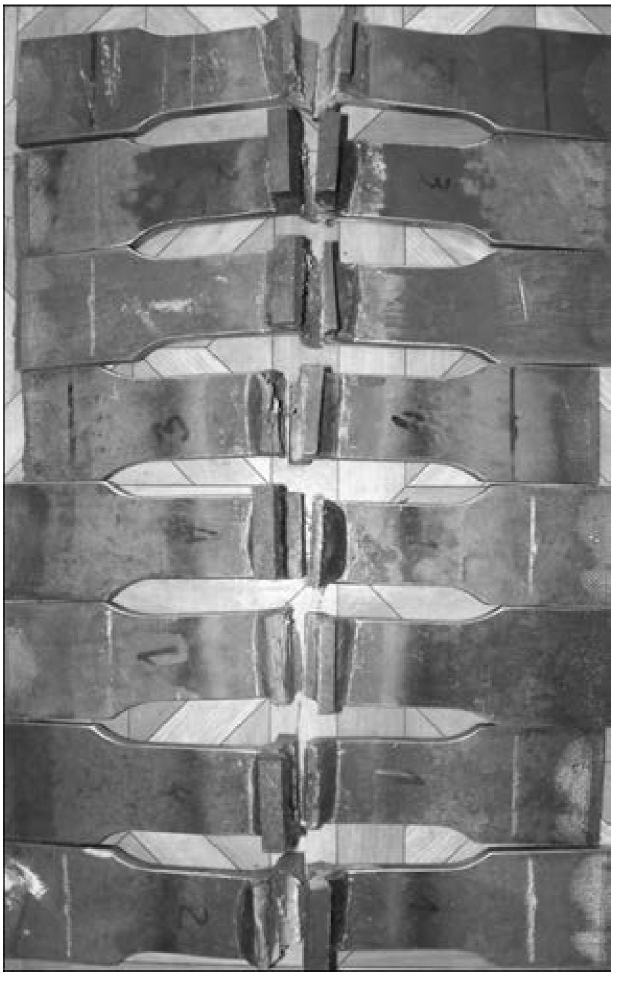

Figure 3. General view of welded T-joints with lack of root penetration which were strengthened by HFMP after fatigue tests

Specimen 5 which was tested under multilevel loading condition (see Figure 2, *a*) failed after running 119.4 thou cycles on the third level of loading (Figure 4, *e*). General running at three levels of loading made 566.9 thou cycles. Welded specimens with full penetration strengthened by HFMP failed along the fusion line [11] in the range of 565.8–1079.8 thou cycles at similar tests.

Specimens 6 and 7 were tested under block loading condition at descending order of load application in each block (see Figure 2, *b*). Failure of the specimens took place after 26.3 thou cycles on second step of the forth block of loading (total amount of cycles up to failure at all levels of loading is 781.2 thou cycles) and after 76.8 thou cycles on fourth step of the second block of loading (total amount of cycles up to failure at all levels of loading is 461.8 thou cycles), respectively. Photos of fatigue fractures are given in Figure 4, *f*, *g*, respectively. Strengthened joints with full penetration failed along the fusion line [12] in the range of 492.3–775.6 thou cycles of stress change at similar tests. High life of the specimen with lack-of-penetration is caused by

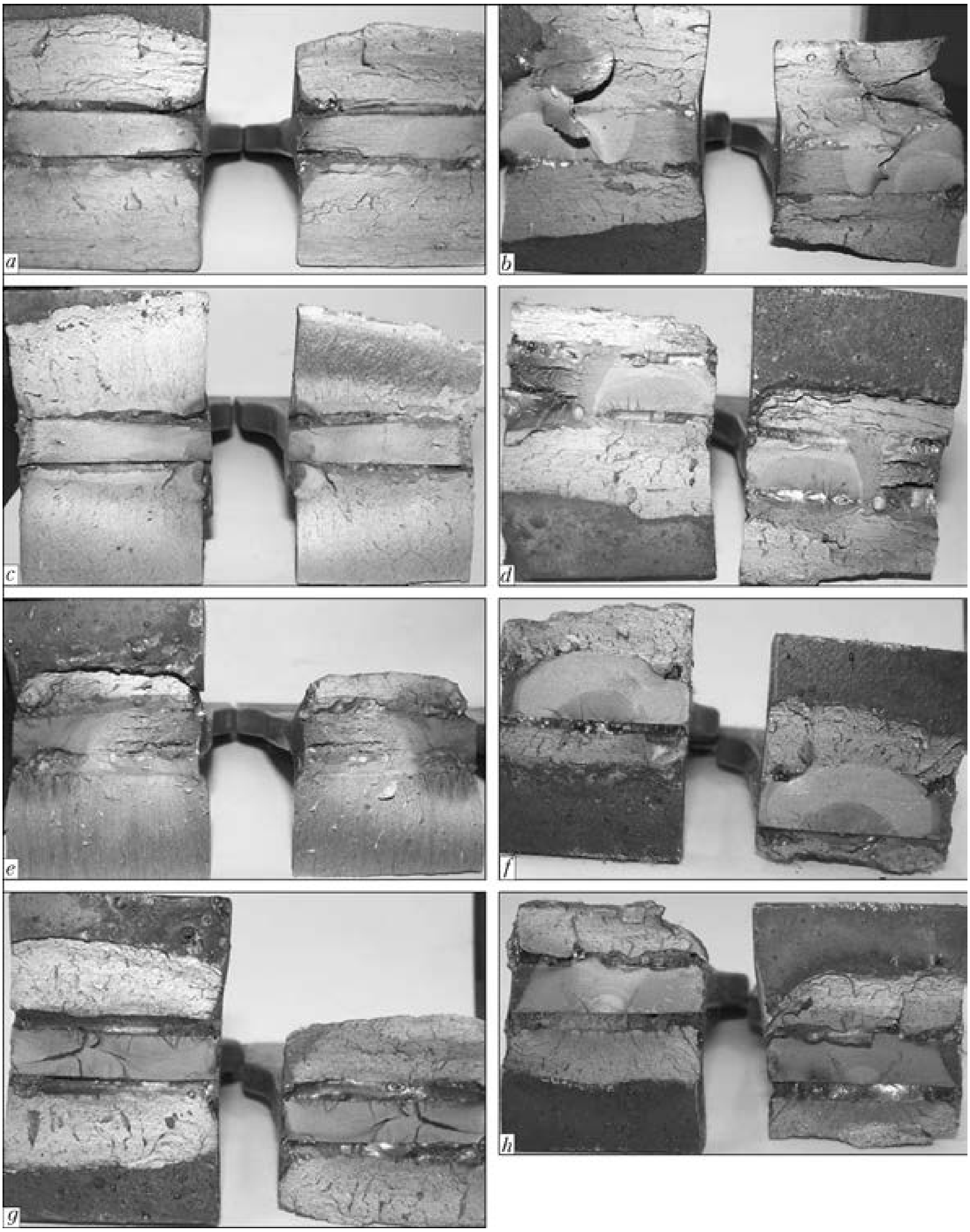

Figure 4. Fatigue fractures of welded T-joints with lack of root penetration: *a*–*h* — specimens 1–8, respectively

development of cracks in the rib and performance of welding of one rib virtually with full penetration as can be seen from Figure 4, *g*.

Specimen 8 was tested under conditions of block loading with quasirandom order of load application in each block (see Figure 2, *c*). The failure of the specimen took place after 54.4 thou cycles on second step of the third block of loading (total amount of cycles up to failure at all cycles of loading was 58.26 thou cycles). Welded specimens with full penetration strengthened by HFMP failed along the fusion line in a range of 578.2–737.8 thou cycles of stress change [12] at similar tests.

Visual analysis of the fatigue fractures of welded T-joints (see Figure 4) showed that the lacks-of-penetration were successfully embedded along the whole width (length of the weld) of the specimens from two sides immediately under the welded ribs in a course of their manufacture, except for specimen 7. Consistency of geometric dimensions of lacks-of-penetration is also hold in a range of 2–3 mm (in height as well as in width) virtually along the whole length of the weld in all specimens.

Obtained results showed that the life of welded T-joints strengthened by HFMP with extensive lacks-of-penetration (cross section 3 × × 3 mm) is in a range of spread of experimental data of the specimens with full penetration. This can be explained in the following way.

Development of cracks in the specimens with lacks-of-penetration takes place in the base metal as well as in the rib metal (see Figure 4) while such a development happens only in the base metal along the fusion line in the specimens with full penetration as shown by the results of fractography analysis of the fatigue fractures of the tested specimens. Development of the fatigue crack takes place at lower stresses from external loading due to larger cross section of its development (considering height of the welded ribs) regardless that its nucleation from the lack-of-penetration can happen earlier than in zone of weld transfer to base metal. At that one of its tips develops in weakly loaded rib. Therefore, the failure in lack-of-penetration zone takes place less intensively, virtually, providing no reduction of the life of the joint in comparison with the life of defect-free joints up to complete failure. Significant part of determined fatigue life in the welded joint with lack-of-penetration falls at growth of fatigue crack in the base metal and in metal of welded rib (see Figure 4). Thus, critical crack depth in zone of weld transfer to base metal lies in the range of 4–8 mm in the welded joints with full penetration, while that achieves 12–20 mm in a moment of brittle fracture in strengthened joints with lack-of-penetration.

Such a peculiarity of kinetics of fatigue fracture of T-joints, ribs of which do not transfer main load, strengthened by HFMP and having lack-of-penetration allows significantly increasing their fatigue life using HFMP. At that, the indices of fatigue strength of the joints strengthened by HFMP with lack-of-penetration are at the level of that of strengthened welded joints made with full penetration.

Conclusions

1. It was stated that presence of extensive (along the whole length) lack of root penetration of 3 × × 3 mm cross section in the unstrengthened high-loaded welded T-joints, the cross ribs of which do not transfer main load, provides no effect on fatigue life since formation of cracks, and their development take place in the zone of weld transfer to base metal.

2. It was shown that the fatigue life of high-loaded HFMP-strengthened T-joints from low-alloyed steel containing structural and technological extensive lacks of root penetration of 3 × × 3 mm cross section lies in the range of spread of experimental data for strengthened joints made with full penetration. At that, fatigue life of strengthened joints with lacks of penetration increases up to 10 times in comparison with that of unstrengthened specimens with full penetration.

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