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PROCEDURE OF ACCELERATED CORROSION TESTING FOR MODELING THE LONG-TERM EFFECT OF MODERATE CLIMATE ATMOSPHERE ON WELDED JOINTS

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We propose a procedure of accelerated corrosion testing of welded joints for modeling the long-term effect of the most significant climatic factors of moderate climate atmosphere (temperature and relative humidity) on them. Duration of accelerated testing of welded joints in the humidity chamber to obtain corrosion damage, which is characteristic for welded joints of metal structures after approximately 12 years of operation, is substantiated. Fatigue testing of butt and tee welded joints of 15KhSND steel after preliminary exposure to 2 mln cycles at maximum stresses of 150 MPa, corrosion testing under the conditions of higher temperature and relative humidity without strengthening and with further strengthening by the technology of high-frequency mechanical peening, were performed. It is found that strengthening by the technology of high-frequency mechanical peening improves 10 times the cyclic fatigue life of butt and tee welded joints with accumulated fatigue and corrosion damage. 23 Ref., 5 Figures.

Keywords: *welded joint, corrosive environment, fatigue, accelerated corrosion testing, high-frequency mechanical peening, improvement of cyclic fatigue life*

A considerable part of welded metal structures and constructions in the territory of Ukraine exposed to variable loading in service (bridges, overpasses, cranes, etc.), were put into operation in 1960–1980s. These structures are protected from the impact of climatic environmental factors (corrosion) by paint-lacquer coatings. During long-term operation, however, mechanical damage, cracking and delamination of the lacquer-paint coatings can take place. This leads to welded elements of the structures being exposed not only to variable loading, but also to corrosion impact [1, 2]. Formation of corrosion damage lowers the design thickness of structural elements and fatigue resistance characteristics of welded joints, leading to premature failure [3]. In case of an objective need of further operation of these structures, during performance of repair-restoration operations it is necessary to not only remove the corrosion products and renew the lacquer-paint coatings, but also increase the cyclic fatigue life of welded joints damaged by corrosion by additional strengthening treatment. For a guaranteed improvement of fatigue resistance characteristics of welded joints in metal structures, it is recommended to apply high-frequency mechanical peening (HFMP) [4–8]. To establish the effectiveness of application of HFMP technology for improvement of the fatigue life of welded structures with corrosion damage, it was necessary to model the long-term impact of moderate climate conditions by accelerated testing in the laboratory. Analysis of normative documents showed that until recently the comparative studies of corrosion resistance of structural steels under atmospheric conditions were conducted in Ukraine in keeping with the procedures specified in the normative documents [9–11]. After cancellation of GOSTs European norms began to be introduced [12, 13]. However, both in the GOSTs and in the current standards [9–14], just the test conditions or a set of test conditions modeling the impact of corrosive factors are proposed, but information on the duration of sample exposure is absent.

Therefore, the objective of this work is development of a procedure of accelerated corrosion testing for modeling the long-term impact of moderate climate atmosphere on the welded joints and establishing the effectiveness of application of HFMP technology to improve its cyclic fatigue life.

Development of the procedure of accelerated corrosion testing. The procedure of accelerated corrosion testing of the samples was developed for moderate climate of Ukraine. The corrosion processes were essentially affected by the duration of the cycle of surface wetting, during which a film of moisture is present on the structural elements [15, 16]. In [17] the moderate climate is characterized by temperature range from –33 to +35 °C, and the calculated time of moderate humidity above 80 % at temperatures above 0 °C is equal from 2500 to 4200 h/y. The corrosion processes are the most active in the presence of phase films of moisture that form at the metal surface wetting by liquid precipitation or condensate. In keeping with the data of work [16], for moderate climate characteristic for the central regions of Ukraine, wetting by phase film amounts to 2520 h/y. Here, the annual average temperature in this region is equal to 11 °C [18]. In the normative documents [9–14], in order to model the influence of climatic factors on metal corrosion, it is recommended to perform sample exposure under the conditions of higher temperature and humidity, salt spray or cyclic impact of these factors. As the presence of chlorides in the environment and their impact on metals is more characteristic for marine climate (coastal zone of Ukraine), then at development of the procedure of conducting accelerated corrosion testing only such factors were taken into account, as higher temperature and humidity. The impact of these factors was modeled under laboratory conditions in G4 hydrostat (humidity chamber).

According to the data of [10, 12] for carbon and low-alloyed structural steels, the temperature in the hydrostat should be maintained on the level of 40 °C, so as not to change the mechanism of the corrosion processes. Here, air humidity (in the absence of forced circulation of air) is close to 100 % that ensures formation of phase films of moisture, which initiate the corrosion processes during the entire time of exposure.

It is known that at the change of temperature from the initial to higher one, the reaction rate, including the corrosion rate, rises by Van’t Hoff law [19]:

$$V_{t_2} = V_{t_1}\gamma^{\frac{t_2-t_1}{10}}, \qquad (1)$$

where V_{t2} is the reaction rate at higher temperature during performance of laboratory testing t_2 (in our case t_2 = 40 °C, according to [10, 12]); V_{t_1} is the reaction rate at temperature t_1. Temperature t_1 was taken to be the average annual temperature in the central regions of Ukraine, i.e. 11 °C [18]; γ — is the reaction temperature coefficient.

Taking into account the recommended value of temperature coefficient γ = 3, the acceleration of the corrosion process at increased temperature and humidity, according to (1) will be equal to:

$$\gamma^{\frac{t_1-t_2}{10}} = 3^{\frac{40-11}{10}} = 3^{2.9} \approx 24.2, \qquad (2)$$

Thus, the corrosion processes on the metal surface can be accelerated 24.2 times in G4 hydrostat at increased temperature of 40 °C and relative humidity of about 100 %. Considering that during one year the phase film of moisture on the metal surface is observed during 2520 h [16], one year of structure operation will be equivalent to sample exposure in the hydrostat for 2520/24.2 = 104 h.

In welded metal structures in service the corrosion damage of elements is revealed, as a rule during scheduled examinations. At modeling of corrosion damage in the welded joints by an accelerated procedure, it is rational to take into account the maximum interval between examinations of such structures. For instance, for span structures of bridges, the period between the examinations is from 5 [20] up to 10 years [21]. Considering that 1 to 2 more years will pass after examination of such structures and detection of corrosion damage before the beginning of repair-restoration operations, it is rational to model on welded joint samples the corrosion damage which may develop on the surface of welded structural elements after operation for almost 12 years.

Thus, the characteristic corrosion damage of welded structures after 12 years of operation under the conditions of the impact of the most significant climatic factors (temperature and humidity) of moderate climate of the central regions of Ukraine, can be obtained by conducting accelerated corrosion testing in G4 hydrostat at higher temperature of 40 °C and air humidity close to 100 % for 1200 h.

Investigation material and procedure of fatigue testing. Experimental studies were conducted on samples of butt and tee welded joints of low-alloyed steel 15KhSND (σ_y = 400 MPa, σ_t = 565 MPa) which is widely applied for manufacture of elements of long-term metal structures (for instance, in span structures of railway and road bridges), has higher strength, is readily weldable, resistant to atmospheric conditions and serviceable in the temperature range from –70 °C up to +45 °C.

Blanks for welded joint samples were cut out from hot-rolled plates 12 mm thick of category 12 in the rolling direction. The dimensions of blanks for butt joints were 600×180 mm, and of those for tee joints — 350×70 mm. Butt welded joints were produced by single-arc automatic welding of plates without edge preparation from both sides (0–1.0 mm gap in the butt) using OP 192 flux (Oerlikon Company) with 4 mm Sv-08G1NMA wire. Welding was conducted at reverse polarity with power supply from electric rectifier VSZh-1600. Welding modes were as follows: first weld U = 55 V; I = 650–700 A, v = 26.7 m/h; second one (from the reverse side): U = 57 V; I = 660–780 A, v = 26.7 m/h. The second weld was made after complete cooling of the first one. 8 samples of 360×70 mm size were prepared from each welded plate of 600×360 mm size. Tee joints were produced by joining transverse stiffeners (also from steel 15KhSND) from two sides of the

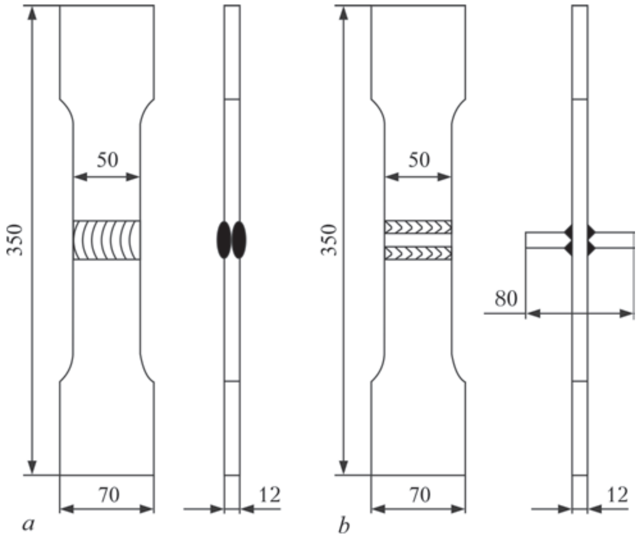

Figure 1. Samples of butt (*a*) and tee (*b*) welded joints

plate by fillet welds, using manual arc welding with UONI 13/55 grade electrodes. The root (first weld) was made by 3 mm electrodes, the second weld was formed by 4 mm electrode. The shape and geometrical dimensions of samples of butt and tee welded joints are given in Figure 1. The sample thickness is due to wide application of 12 mm thick rolled stock in engineering welded structures, and the working part width of 50 mm was selected proceeding from the testing equipment capacity.

The above procedure of conducting accelerated corrosion testing allows modeling the impact of moderate climate for 12 years on the condition of welded structure surface. Thus, it was also necessary to allow for the accumulated fatigue damage under the impact of variable cyclic loading after 12 years of operation. The following was taken into account. The design service life of the majority of welded structures for engineering applications is equal to 50–100 years. Proceeding from the hypothesis of linear accumulation of fatigue damage over 12 years of operation, the welded joints should use 12–25 % of their fatigue life to fracture, which can be determined from fatigue curves of these joints. Fatigue curves of the studied welded joints of 15KhSND steel were derived earlier on the base of testing by 2 mln cycles [22]. Here, the limited endurance limits after $2\cdot10^6$ stress alternation cycles for butt and tee welded joints were equal to 187 and 180 MPa, respectively. However, it is rational to perform fatigue damage accumulation in welded joints at lower levels of applied maximum stresses, which are closer to the working ones. In keeping with the recommendations of the International Institute of Welding [23] the fatigue curves of welded elements of structures have a constant angle of inclination in the range of 10^5–10^7 cycles, that allows continuing the fatigue curve derived in work [22] from $2\cdot10^6$ to 10^7 cycles. The required level of fatigue damage accumulation of 12–25 % was achieved by testing the welded joints in the initial condition by 2 mln cycles at maximum values of applied cycle stresses of 150 MPa (30–37 MPa lower than the experimentally established limited endurance limits of the studied joints).

Thus, for modeling the accumulated fatigue and corrosion damage, characteristic for welded joints after 12 years of metal structure operation, all the samples were first exposed to $2\cdot10^6$ cycles of stress alternation in TsDM 10-pu testing machine at zero-to-stress loading cycle with maximum applied loads of 150 MPa, and then in keeping with the developed procedure, they were exposed in G4 hydrostat at the temperature of 40 °C and relative air humidity of 100 % for 1200 h. After corrosion testing one part of the samples remained unstrengthened, and the other part was strengthened by HFMP technology.

The welded joints were strengthened by HFMP technology using USTREAT-1.0 equipment, in which the manual compact impact tool with a piezoceramic converter is connected to an ultrasonic generator with output power of 500 W. At treatment of welded joints by HFMP technology a narrow zone of weld metal transition to the HAZ (along the fusion line) was subjected to surface plastic deformation. A single-row four-striker attachment with 3 mm diameter of the strikers was used as the strengthening device. Strengthening was conducted without preliminary cleaning of the surface from the corrosion products.

Four series of samples were prepared for fatigue testing:

- samples of butt and tee joints after testing by 2 mln cycles and subsequent corrosion testing, samples of the first and second series, respectively;
- samples of butt and tee welded joints after testing by 2 mln cycles, subsequent corrosion testing and strengthening by HFMP technology, samples of the third and fourth series, respectively.

Experimental studies of fatigue resistance of all the four sample series were conducted in URS-20 testing machine at alternating tension with cycle asymmetry $R_\sigma = 0$ and 5 Hz frequency at regular loading. Complete fracture of the samples or exceeding the test base of $2\cdot10^6$ cycles of stress alternation was taken as the test completion criterion.

Investigation results. After testing in the hydrostat, the welded joint samples were covered by a nonuniform layer of corrosion products of brown colour with embedded corrosion products of black colour. Sample cleaning to remove the corrosion products was not conducted after corrosion testing. As a result of strengthening by HFMP technology a characteristic groove without corrosion products formed along the line of weld metal transition to base metal (Figure 2). Results of fa-

Figure 2. Appearance of weld zone of a tee welded joint of 15KhSND steel after testing by 2·10^6 cycles, corrosion testing for 1200 h in the hydrostat and strengthening by HFMP technology

tigue testing of samples of butt and tee welded joints of 15KhSND steel are given in Figures 3 and 4, respectively. Results of testing welded joints in the initial condition (without the impact of the corrosive environment), derived earlier in work [22], are also given there.

It is experimentally established that fatigue resistance characteristics of butt welded joints after cyclic loading (2·10^6 cycles of stress alternation) and further exposure to higher temperature and humidity of air for 1200 h (first series) are on the level of welded joints in the initial condition, tested in air (Figure 3, curves *1*, *2*). Fracture of all the samples of the first series occurred along the line of transition of the weld to base metal. Strengthening by HFMP technology (third series) increases the limited endurance limits of such joints on the base of 2·10^6 cycles by 33 % (from 187 up to 248 MPa), compared both to joints in the initial condition, and those with the specified level of accumulated fatigue and corrosion damage without strengthening (Figure 3). Here, cyclic fatigue life of the strengthened welded joints increases 10 times. Fracture of all the samples of the third series occurred mainly through the base metal at a distance from the fusion zone (Figure 5, *a*).

Characteristics of fatigue resistance of tee welded joints after cyclic loading and corrosion testing for 1200 h (second series) dropped by 25 % (from 180 to 135 MPa), compared to joints in the initial condition, tested in air (Figure 3, curves *1*, *2*). Fracture of all the samples of the second series occurred along the line of weld to base metal transition. Strengthening by HFMP technology (fourth series) significantly increases fatigue resistance characteristics: limited endurance limit of such joints on the base of 2·10^6 cycles increases by 31 % (from 180 up to 236 MPa), compared to samples in the initial condition, and cyclic fatigue life increases 8 times. Compared to second series samples (with the set level of fatigue and corrosion damage accumulation, without strengthening), the limited endurance limit on the base of 2·10^6 cycles of samples of the fourth series increases by 75 % (from 135 up to 236 MPa), whereas cyclic fatigue life increases 10 times (Figure 4). Fracture of samples of the fourth series occurred both along the fusion line, and in the base metal away from the weld (Figure 5, *b*). One sample failed from incomplete penetration of the weld root along the stiffener, but its

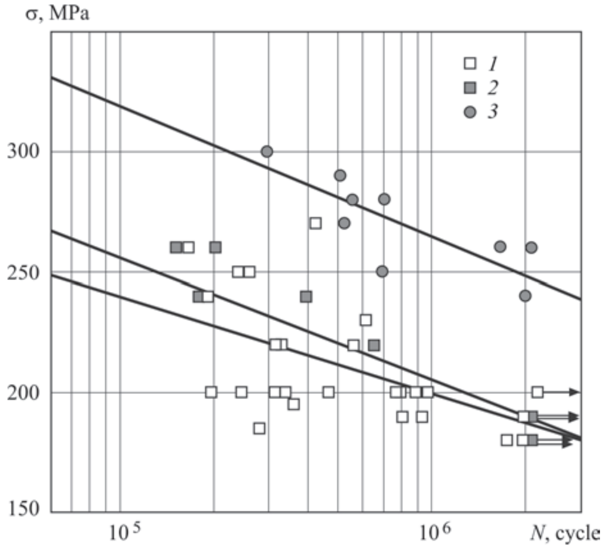

Figure 3. Fatigue curves of butt welded joints of 15KhSND steel: *1* — in the initial condition [22]; *2* — after testing by 2·10^6 cycles at maximum stresses of 150 MPa and corrosion testing for 1200 h (first series); *3* — after testing for 2·10^6 cycles at maximum stresses of 150 MPa, corrosion testing for 1200 h and further strengthening by HFMP technology (third series)

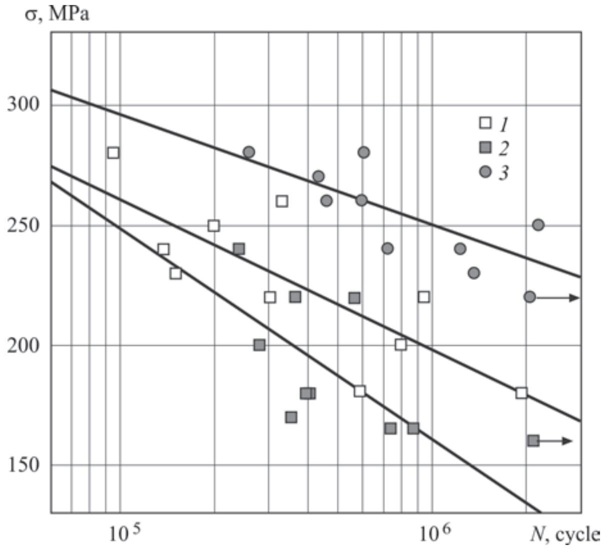

Figure 4. Fatigue curves of tee welded joints of 15KhSND steel: *1* — in the initial condition [22]; *2* — after cyclic testing at maximum stresses of 150 MPa and corrosion testing for 1200 h (second series); *3* — after testing by 2·10^6 cycles at maximum loads of 150 MPa, corrosion testing for 1200 h and further strengthening by HFMP technology (fourth series)

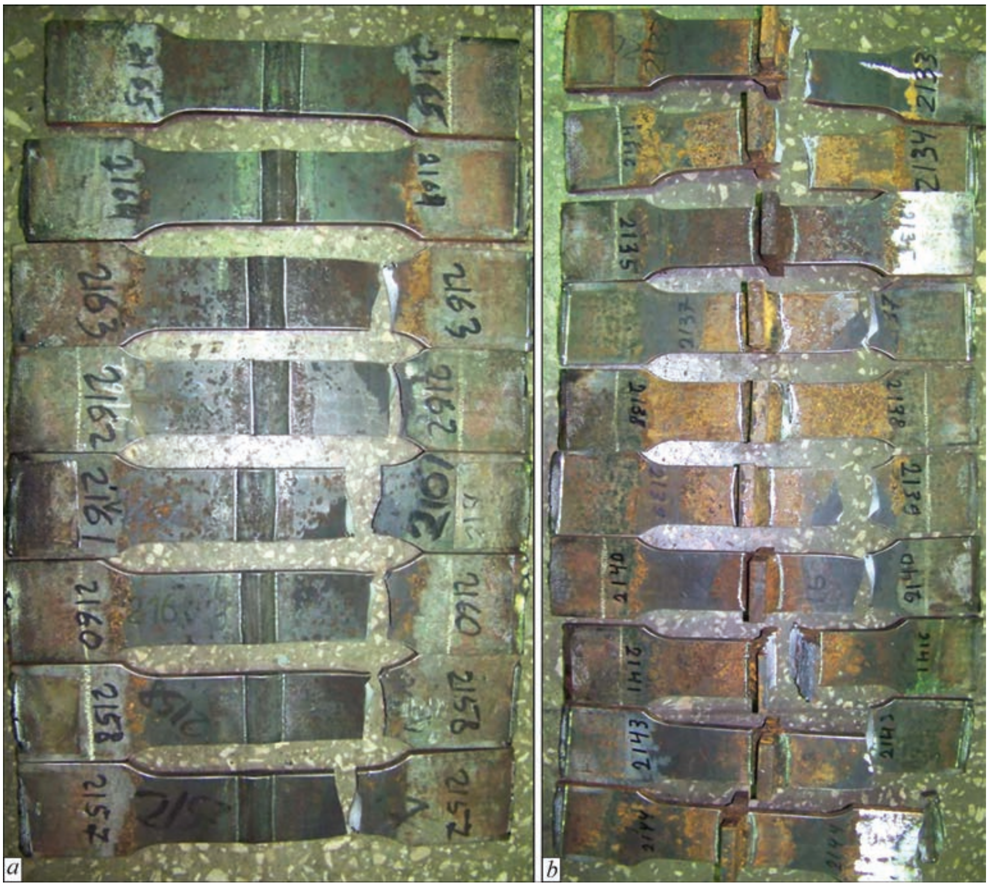

Figure 5. Appearance of samples of the third (*a*) and fourth (*b*) series after fatigue testing

cyclic fatigue life remained within the range of data scatter for sound welded joints.

Thus, obtained experimental results are indicative of the high effectiveness of HFMP technology application to improve the fatigue resistance characteristics of butt and tee welded joints of metal structures after their long-term operation under the conditions of variable loading and moderate climate atmosphere.

Conclusions

1. A procedure was developed for accelerated corrosion testing of welded joints in order to model the long-term impact on them of the most significant climatic factors (temperature and relative humidity) of moderate climate of the central regions of Ukraine. Rationality of modeling the corrosion damage forming on the surface of welded structure elements after 12 years of operation was substantiated. It is proposed to produce such corrosion damage of welded joint by conducting accelerated corrosion testing in G4 hydrostat at higher temperature of 40 °C and relative air humidity of 100 % for 1200 h.

2. It is established that strengthening by HFMP technology of butt welded joints of 15KhSND steel after preliminary testing by 2 mln cycles at maximum stress levels of 150 MPa and exposure under the conditions of higher temperature and humidity of air for 1200 h leads to 10 times increase of cyclic fatigue life and increase of the limited endurance limit on the base of $2\cdot10^6$ cycles by 33 % (from 187 to 248 MPa).

3. Shown is the high effectiveness of strengthening by HFMP technology of tee welded joints of 15KhSND steel with the set level of accumulated fatigue and corrosion damage: limited endurance limit on the base of $2\cdot10^6$ cycles increases by 75 % (from 135 up to 236 MPa), and cyclic fatigue life increases 10 times.

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