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EFFICIENCY OF DIFFERENT METHODS OF STRENGTHENING TREATMENT OF WELDED JOINTS

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The efficiency of selection of non-damaging modes of vibration treatment of welded elements of low-carbon steel metal structures with the purpose of reducing residual stresses in them without danger of fatigue fracture at the stage of technological treatment is shown. The comparative fatigue investigations showed an increase in the service life of vibrotreated welded joints and an increase in their fatigue limit at the increase of test base. A method for determination of fatigue limits for butt welded joints of low-carbon steel after different modes of high-frequency mechanical peening, using experimental data of groove depth measurement, was proposed. The efficiency of increasing their fatigue limit is shown depending on the speed of high-frequency mechanical peening and the amplitude of oscillations of the working tool. The results of experimental investigations of increasing fatigue resistance of welded joints of low-alloy and low-carbon steels under harmonic and repeated impact loading at the temperature of –60 °C after high-frequency mechanical peening, argon-arc, explosive, and mechanical treatments were analyzed and a comparative analysis of their efficiency was presented. 23 Ref., 4 Tables, 10 Figures.

Keywords: *welded joint, fatigue resistance, fatigue limit, residual stresses, depth of groove, speed of peening*

Until now a large experience in using different technological methods of increasing the fatigue resistance of welded joints has already been gained [1–3]. The application of this or that method is connected with the peculiarity of production, the availability of technological equipment, operating conditions and so on. However, many of them require their optimization and conducting of additional investigations. This fully concerns vibration treatment (VT) [4] and high-frequency mechanical peening (HMP) [5] of welded elements of metal structures.

The analysis of works, devoted to the vibration treatment showed that it is used to reduce tensile residual stresses (RS), which can decrease the service life of the product [1], or change its shape [6]. Its advantage is in the fact that when subjecting the entire structure to cyclic loading as a whole, RS decreases in the elements, having different rigidity, in one technological cycle. However, the disadvantage of VT is that the value of variable stresses in the structures, created by mechanical vibrators, is selected experimentally [7, 8].

High-frequency mechanical peening of different types of welded joints provides a considerable increase in their fatigue resistance and service life [9], including the conditions of low climatic temperatures due to strengthening of a narrow zone at the transition of weld to base metal. At present, a notable progress has been achieved in the search for a reliable criterion, reflecting its efficiency. Instead of speed of the working tool displacement along the weld [10, 11], the procedure was proposed for evaluating the increase in fatigue limits by groove depth [12], formed after HMP, and the parameters of HMP speed were proposed depending on the amplitude of the working tool oscillations. However, up to the present time, the effect of different treatment modes on fatigue resistance of welded joints remains not investigated.

The aim of this work was the optimization of different types of strengthening treatment of welded joints, experimental evaluation of their effect on fatigue resistance of welded specimens and elements of metal structures.

Objects of investigation, testing equipment. The investigations of effect of types of strengthening treatments were carried out both in laboratory conditions on welded specimens of low-alloy and low-carbon steels with butt and T-joints, as well as in the industrial conditions on welded girders of box-type section (further girders) of sheet steel of 20 mm thickness, modeling the structure of a locomotive diesel underframe. The used grades of rolled steel, basic dimensions of specimens and their mechanical properties are given in Table 1.

The specimens were cut out either of welded workpieces with the dimensions in plane of 400x660 mm, where butt joints were made by manual electric arc welding (steel 14Kh2GMR) or by semi-automatic welding in carbon dioxide (steel 12GN2MFAYu, St.3sp (killed), and T-joints were made by automatic submerged arc welding (steel 15KhSND and 09G2S), or individually with a stiffener welded-on

Table 1. Basic dimensions of welded specimens and mechanical properties of steels at room temperature

Steel grade, type of joint	Dimensions, mm						σ_y, MPa	σ_t, MPa
	h	*b*	*L*	*e*	*k*	*H*		
14Kh2GMR, butt	16	80	400	12	–	–	702	800
12GN2MFAYu, butt	24	40	400	–	–	–	620	710
15KhSND, T-joint	14	80	400	12	14	40	435	600
09G2S, T-joint	20	40	400	–	20	36	340	520
Steel 20, with longitudinal stiffener	20	100	400	–	12	40	290	440
Steel 20, girder	190	170	2100	–	–	–	290	440
St.3sp, butt	14	40	400	–	–	–	300	470

Note. *h*, *b*, *L* — thickness, width, length of specimen; *e* — width of surfacing; *k*, *N* — thickness and height of welded-on stiffener.

using semiautomatic welding along the long side of the specimen in carbon dioxide (steel 20). In order to obtain the fatigue limits of welded structures by the results of testing specimens, the latter must have high residual stresses, which were created by surfacing a longitudinal bead on the specimen back side, or by its half-thickness immersion into water. The residual stresses in girders of steel 20 were induced by applying longitudinal surfacing on the edges, and stress concentrators — by welding-on special cover plates in the tensile RS field. The value and sign of RS in the direction coinciding with the direction of the load applying were determined by the magnetic-noise method based on the Barkhausen effect [13]. Considering that in the near-weld zone the material undergoes structural changes as a result of welding, a series of calibration curves was preliminarily plotted to improve the accuracy of evaluating the value and distribution of RS. Each curve was determined at that distance from surfacing, at which determination of RS took place.

The fatigue tests of specimens were carried out during bending under the conditions of a preset coefficient of asymmetry of the stress cycle R at the harmonic loading in the mode of a given deformation amplitude and repeated impact loading in the mode of a preset impact energy at the temperature of –60 °C [14]. The amplitude of stresses was measured applying strain gauge method. At low-temperature tests, the specimens were cooled by a regulated supply of liquid nitrogen through the holes specially made in them. As the criterion of fracture of specimens, the formation of limited crack length on the surface, equal to 10 mm, which corresponds to its subcritical depth of about 2.5 mm [3], or their brittle fracture at a shorter crack length, was accepted.

The vibration treatment of girders was carried out both by means of electromechanical vibrator IV 107 by creating variable stresses at the resonance or near-resonance frequencies, as well as by pulsator TsDM-200Pu in the mode of forced oscillations, which allow testing at any asymmetry of the cycle. The amplitude of stresses was measured applying strain gauge method. During tests, three-point and cantilever loading schemes were used.

The fusion line of weld with the base metal was subjected to high-frequency mechanical peening by means of ultrasonic magnetostriction transducer [15] at a frequency of oscillations of 24.5 kHz, excited by the generator UZG-10M of the 1.2 kW power consumption. Then the ultrasonic piezoceramic tool USP-300 [16] was used with oscillation frequency of 22.0 KHz. The deforming mechanism of both instruments represented a special head with built-in four steel rods of 2.8–3 mm diameter. After HMP a groove of 3.5 mm width is formed with a depth *h*, depending on the speed *V* of the working tool displacement along the weld (peening speed), which was determined as the ratio of length of weld treated to treatment time. At each speed, at least two specimens were treated and the value of groove depth was determined as the arithmetic mean.

Results of investigations and their discussion. *Analysis of vibration treatment efficiency.* The optimization of vibrotreatment procedure, which consists in selecting the non-damaging loading modes to reduce RS, was tested on the example of testing welded girders of steel 20 (see Table 1). To determine the complex diagram of limiting stresses of the cycle (DLSC), necessary for this purpose, the specimens of steel 20 with the stiffener welded-on along the long side of an edge were used. The welding-on of stiffener applying semiautomatic method in the carbon dioxide environment at the immersion of specimen into the water to half of its thickness allowed creating high tensile RS stresses, equal to 0.76 of yield strength of the material σ_y. at the boundary of the weld to the base metal. The carried out fatigue tests in the conditions of harmonic loading at the values *R*, equal to 0 and 0.7 (line *1*), and the cylindrical specimens for cyclic creep at $R = 0.7$ and 0.85 (line *2*) allowed determining the area (shaded) of safe loading from the point of view of fatigue fracture (Figure 1). From the top and bottom it is limited by the lines of fatigue limits 1 and the limits of cyclic creep σ_{ccrR} [17] 2, respectively. The Figure shows a part of the diagram. The values of σ_{ccrR} were determined at

ε_{pl} = 0.2 % under the conditions of tension, since, taking into account the cross-section dimensions of the vibrotreated girders, the stress gradient is equal to zero. The selection of stresses from external load on the condition that the maximum stresses (taking into account the residual stresses) are lower than the line *1*, will provide the absence of fatigue damages, and above the line *2* it will provide the process of effective reducing of RS. Before the beginning of tests on the width of girders, the diagrams of the initial RS were determined. As an example, Figure 2 shows one of them. The asymmetry of the left and right parts of the diagram is explained by the order of application of deposits. The higher RS indicate that on this area the deposits of girders were produced the last. Later, analyzing the kinetics of RS, the value of initial maximum residual tensile stress σ^{i}_{res} was used. In Figure 1 two variants for reducing RS are shown. In the first batch of girders at the value σ^{i}_{res} = 245 MPa (*p. A*), its reduction was carried out under the conditions of a symmetrical stress cycle. This type of loading is provided by vibrator. The duration of VT at the near-resonant frequency, equal to 95 Hz, was approximately 20 min, which corresponded to 10^5 cycles of loading. The end of the process was judged by change in the current consumed by the vibrator. At the maximum admissible amplitude of stresses σ_a = 40 MPa, the decrease in RS occurred down to (0.6–0.62) σ_y(*p. A_1*). It should also be noted that when the value of the initial RS is equal to 120 MPa and amounts to 0.41 σ_y, VT does not lead to its change (curve *2* in Figure 2). Taking into account the opinion accepted in the literature [3] that RS, equal to 0.5 σ_y, do not already influence the fatigue limit, then the necessity of their further reduction is obvious. However, for this it is necessary to increase the amplitude of stresses (section *AB*) to such an extent that along with their reduction, a fatigue fracture of the construction can occur. Therefore, to effectively reduce them (especially if RS are already negligible in the initial state), the application of an asymmetric vibrational load is necessary. For this purpose, the second batch of girders was tested in the pulsator TsDM-200pu (version 2) at an asymmetric cycle of harmonic loading. At the value of σ^{i}_{res} = 200 MPa (*p. C*), the parameters of the external load were calculated (the values are shown in Figure). In contrast to the symmetrical cycle, in this case it is possible to achieve a much higher maximum stress (*p. K*), keeping the condition of safe loading. The RS, determined in several girders, decreased to about σ^{c}_{res} = 145–155 MPa (*p. C_1*), which corresponds to (0.5–0.52)σ_y. Thus, asymmetric loading allows a significant expansion of the capabilities of VT by increasing stresses from the external load, leaving them in a safe region. It is seen that the vibrator treatment reduced the initial RS on average by 20 %, and applying pulsator — by 32 %, which amounted to 0.61 and 0.51 of the yield strength, respectively. As a comparison, the RS values in the girders after heat treatment, corresponded on average to 0.35 σ_y.

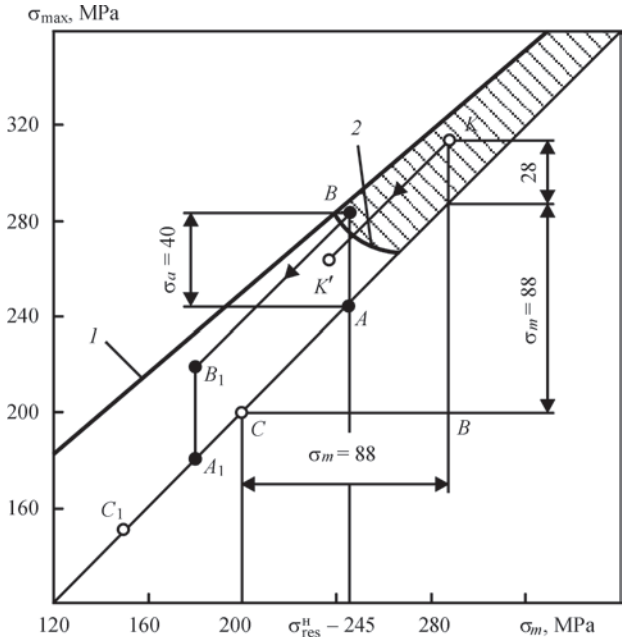

Figure 1. Decrease of RS in welded girders of box section of steel 20 (*1* — line of limiting stresses; *2* — line of limits of cyclic creep of material under tension)

To evaluate the effect of low RS, comparative fatigue tests of specimens were carried out. Preliminarily, the initial RS were reduced in them by non-damaging loading modes to the level equal to 0.5 σ_y. The analysis of the obtained results of investigation at harmonic zero loading under the conditions of room temperature (Figure 3) indicates an increase in the fatigue life of specimens after VT throughout the whole range of stresses application (curve *2*). For comparison, the Figure shows also the fatigue curve of specimens with high residual stresses in the initial state (curve *1*). It

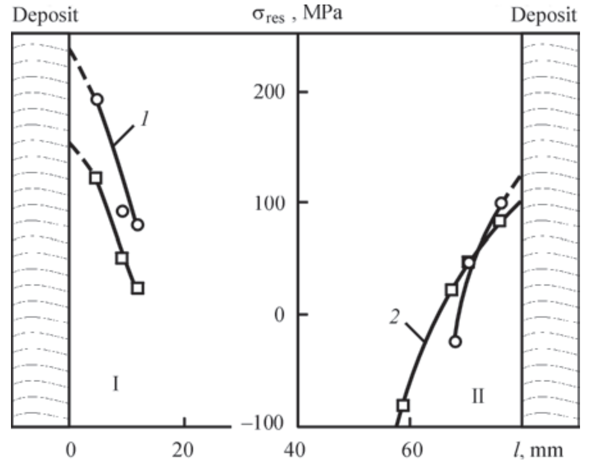

Figure 2. Distribution of RS across the width of the girder with longitudinal deposits in initial state (*1*) and after VT (*2*)

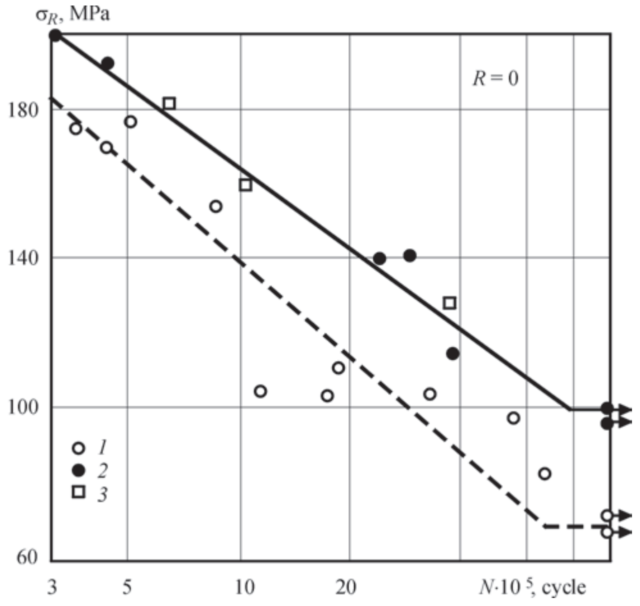

Figure 3. Fatigue curves of steel 20 welded specimens with welded-on stiffener in the initial state (*1*), after VT (*2*) and heat-treatment (*3*)

is seen that with lowering of the load, the effect of residual stresses is manifested to a greater extent, as a result of which the fatigue life of vibrotreated specimens increases with increase in the testing base as compared to the initial state, and the fatigue limit increases. For example, on the basis of $2\cdot10^6$ and $5\cdot10^6$ cycles of loading, it increased by 27 and 40 %, respectively.

In order to evaluate the fatigue life of specimens at even lower values of RS, the specimens subjected to tempering at 600–620 °C were tested. The maximum RS in them was about 0.35 σ_y. It is seen that the points lie on the fatigue curve of the vibrotreated specimens

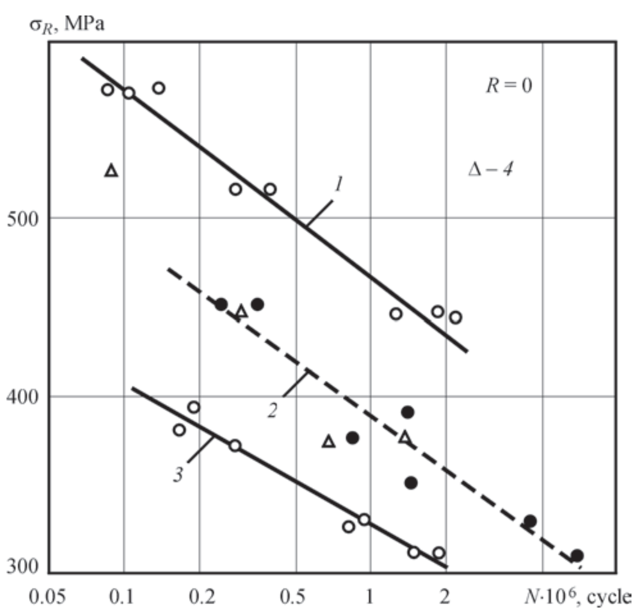

Figure 4. Fatigue curves of steel 09G2S T-joints in the initial state (*2*, *3*), after HMP (*1*, *4*); under the conditions of harmonic loading at the room temperature (*2*) and impact loading at –60 °C (*1*, *3*, *4*)

not badly. The similar results were obtained in the comparative fatigue tests of the joining girders of 120-ton railway tank [18]. Based on the results of specimen tests, a similar increase in fatigue resistance and an increase in the fatigue life of steel structures after VT in the real conditions of their service can be assumed.

Therefore, the carried out tests showed that to increase the fatigue life and fatigue resistance of non-critical structures of low-carbon steel, it is not necessary to apply an expensive procedure of heat treatment in all the cases for maximum reduction of RS in them.

However, the experience in operation of many metal structures demonstrates their fatigue fracture in a narrow weld-to-base metal transition zone. This task is successfully solved by a high-frequency mechanical peening.

Analysis of efficiency of high-frequency mechanical peening. The earlier investigations [12] allowed suggesting the optimal treatment mode, in which the groove depth is provided after a peening of weld zone of at least 0.14 mm. On the basis of the obtained dependences, it follows that to such depth of the groove the speed of the working tool movement along the weld V = 0.065 m/min at the amplitude of oscillations of the waveguide end a = 19 μm and 0.092 m/min at 26 μm corresponds. This is well illustrated by the results of comparative fatigue tests of T-joints of low-alloyed steel 09G2S (Figure 4) and butt joints of low-carbon steel St.3sp (Figure 5) under the conditions of harmonic loading at a room temperature and impact loading at –60 °C. After cutting the welded workpiece on specimens, the latter (see Table 1) were subjected to HMP. The analysis of the data (Figure 4) indicates that in the initial state the fatigue resistance under the conditions of repeated impact loading at –60 °C (curve *3*) is lower than the harmonic loading and room temperature (curve *2*). The fatigue limits, determined on the basis of $2\cdot10^6$ load cycles, were 307 and 360 MPa, respectively. The strengthening of specimens at the speed of peening to higher than the recommended one showed that their resistance to fatigue under the conditions of repeated impact loading is somewhat increased, but it did not exceed the fatigue resistance in the initial state under harmonic loading. The points lie on the fatigue curve *2*. HMP, performed in strict accordance with the speed recommended in the work, provided a significant increase in the fatigue resistance under the conditions of impact loading throughout the whole investigated range of fatigue life (curve *1*). The fatigue limit increased by 21 % as compared to the data of tests of specimens in the initial state under the conditions of harmonic loading. The analysis of results of tests of steel St.3sp welded joints (Figure 5), treated at a peening speed equal to 0.065 m/min, showed that the fatigue limit was 375 MPa (curve *1*), which is by 87 % higher than that obtained during tests of specimens in the initial state (curve *2*). During deviation from the recommendations regarding the speed of peening and violation of HMP technology, there were metal overlays on the weld — «ripples», which were the powerful sources of stress concentration. In this case, the fatigue crack developed from these ripples. The similar results were obtained in the work [19]. As a result, the fatigue life of such specimens increased on average by 2.5 times in comparison with the initial state, and the increase in the fatigue limit was only 11 % (curve *3*).

It is known that as a result of HMP, deformation strengthening of material occurs at some depth from the surface of the groove. Obviously, to different modes of treatment not only the different depth of plastically deformed layer will be corresponded, but also the different depth of a groove *h*. The influence of different treatment modes on fatigue resistance was determined on the example of tests of steel St.3sp welded butt joints (see Table 1). After cutting of welded workpiece into specimens, the latter were subjected to HMP at the amplitude of oscillations of working tool a = 19 μm and to the given speed of its displacement V, equal to 0.232, 0.116 and 0.06 m/min, respectively. After strengthening, a groove with width of 2.8–3.5 mm and a depth of 0.041, 0.062, and 0.143 mm, respectively, was formed depending on the speed of treatment. The analysis of influence of groove depth on the strengthening effect, expressed in increasing fatigue limit of welded joint, was made on the basis of Figure 6, in which the experimentally determined fatigue limits of welded butt joints in the initial state (σ^{i}_R = 200 MPa) and at the speed of HMP equal to 0.065 m/min (σ_R = 375 MPa), at a = = 19 μm (see Figure 5), as well as the corresponding values of the groove depth are noted. The calculated dependence of the fatigue limit of welded joints on the current groove depth h_{i} in this case has the following form

$$\sigma^{i}_R = \sigma^{\mathrm{i}}_R + Kh_i = \sigma^{\mathrm{i}}_R + \frac{\sigma_R - \sigma^{\mathrm{i}}_R}{h} h_i, \qquad (1)$$

where $K = \frac{\sigma_R - \sigma^{\mathrm{i}}_R}{h}$ is the correlation coefficient; h_i is the current value of the groove depth obtained after different speed of HMP.

From the known values of fatigue limits of welded joints and the experimentally established h = = 0.143 mm, we found that $K = 1.224 \cdot 10^3$ MPa/mm. Through calculations the proposed expression allows evaluating the fatigue limit of welded joint (darkened points) at any depth of the groove without carrying

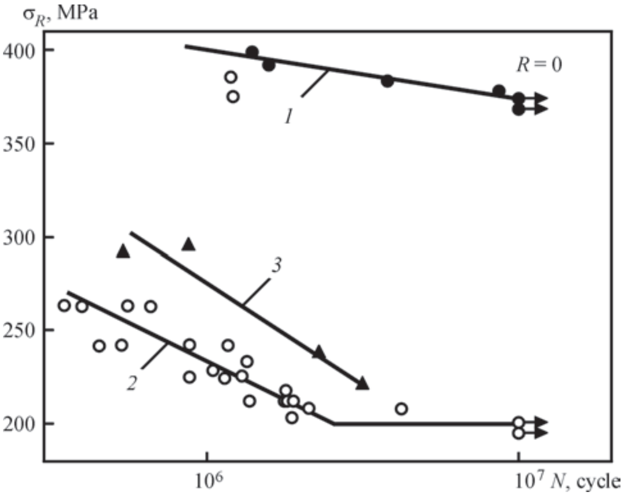

Figure 5. Fatigue curves of butt joints of steel St.3sp: *1* — according to the recommended speed of peening; *2* — in initial state; *3* — with deviation from the recommended HMP technology

out labor- and time-consuming tests. The calculated values σ^{i}_R are given in Table 2. The assumption about the proportional increase in the fatigue limit of a strengthened welded joint with increase in h_i requires further experimental confirmation. However, in favor of its proportional increase both the test data of strengthened specimens from literature [20] and the available information on the proportional dependence between the groove depth and the fatigue life of welded joints [12] evidence. It should be noted that the groove depth represents an integral characteristic which indirectly reflects the depth of the plastically deformed layer and the corresponding compression RS. The depth of the groove obtained in the work [12] for this thickness of welded joint is considered as an optimal, since its further increase may not be accompanied by strengthening and the probability of peeling of the strengthened surface is increased that negatively effects the fatigue resistance of specimens. As to the stress concentration coefficient, then the earlier investigations showed [21], that the share of its influence in totality of all factors is only 14 %.

It is known that the groove depth largely depends on the amplitude of the working tool oscillations. As practice showed, most often welded elements of metal structures are treated at a, varying in the range from 19

Table 2. Dependence of fatigue limits of butt joints on groove depth and the corresponding speed of HMP at different amplitude of working tool oscillations

Depth of groove h_i, mm	Limit of fatigue σ^{i}_R, MPa		Speed of HMP (m/min) at the amplitude of oscillations	
	Calculation	Experiment	a = 19 μm	a = 26 μm
0.041	251	–	0.4	0.4
0.062	278	–	0.11	0.24
0.1	325	–	0.075	0.125
0.143	379	375	0.06	0.092

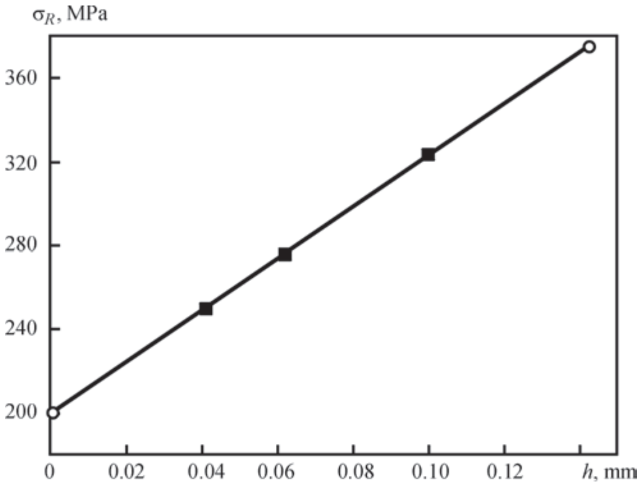

Figure 6. Calculated (*dark points*) and experimental (*light points*) dependence of fatigue limit of strengthened butt welded joints on the groove depth

to 26 μm. In this connection, using previously obtained dependences of groove depth on the speed of HMP at the amplitudes of 19 and 26 μm [12], Figure 7 shows the summary diagram on which the dependences between the groove depth and the fatigue limit of welded joints (Table 2) are presented on one side and between the groove depth and speed of peening for different amplitude of oscillations of working tool on the other, respectively. The analysis of the results presented in such a form allows determining not only the change in the groove depth at a given peening speed depending on the amplitude of oscillations of working tool, but also the fatigue limit of welded joint. It follows from the diagram that as the speed of treatment increases, the groove depth decreases, and the effect of amplitude of oscillations of working tool on the strength characteristics becomes less effective, since the curves *1* and *2* are practically converged. At $V = 0.4$ m/min h practically does not depend on a, which in its turn determines the same values of

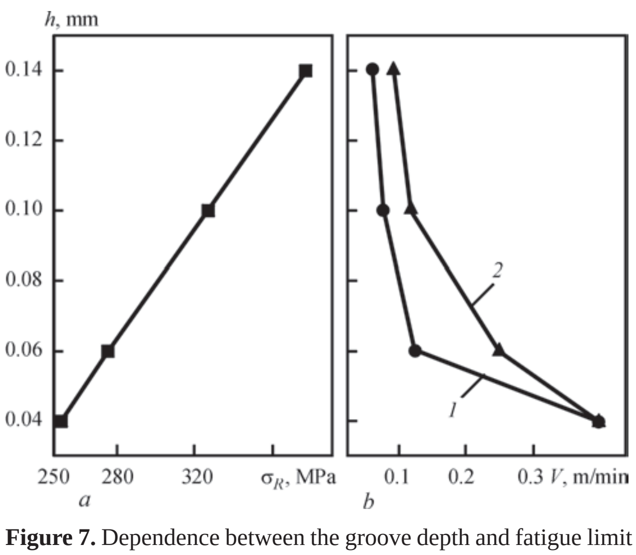

Figure 7. Dependence between the groove depth and fatigue limit of strengthened welded joints (a), and also the speed of HMP at the amplitude of working tool oscillations of 19 (*1*) and 26 μm (*2*) (b)

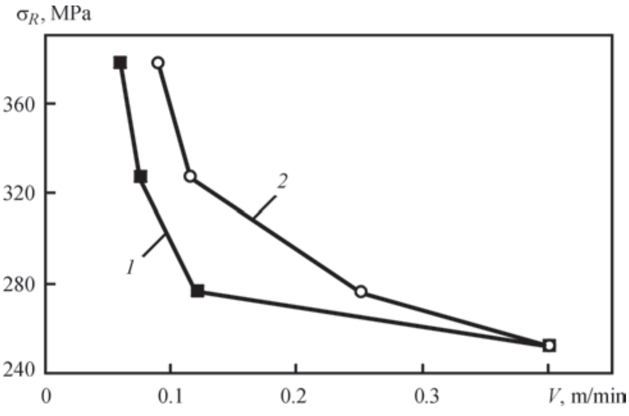

Figure 8. Dependence of fatigue limits of welded joints on the speed of HMP at the amplitude of working tool oscillations of 19 (*1*) and 26 (*2*) μm

fatigue limits of welded specimens. The obtained effect can have a practical importance in using this strengthening technology.

Often, during repair and restoration works in hard-to-reach places of structural elements it is not always possible to determine the groove depth reliably, but it is easier to fix the speed of peening. In this connection, Figure 8 shows the dependences of fatigue limits of welded joints on the speed of peening, determined at the amplitude of oscillations of working tool of 19 and 26 μm, respectively. It is seen that with increase in V, not only their decrease occurs, but also a decrease in difference between them. In addition, at $V =$ $= 0.4$ m/min, the values σ_R are the same independently of a, but 25 % higher than the fatigue limit of welded joint in the initial state.

The relative increase in σ_R of welded joints, determined after a different speed of HMP in the range of varying a from 19 to 26 μm, illustrates well the dependences shown in Figure 9. Their calculated values at the current amplitude of oscillations of working tool a_i can be determined from the equation

$$\frac{\sigma_{Ri}}{\sigma_R^{\mathrm{i}}} = \frac{\sigma_{R1}}{\sigma_R^{\mathrm{i}}} + \frac{\sigma_{R2} - \sigma_{R1}}{\sigma_R^{\mathrm{i}}(a_2 - a_1)}(a_i - a_1), \qquad (2)$$

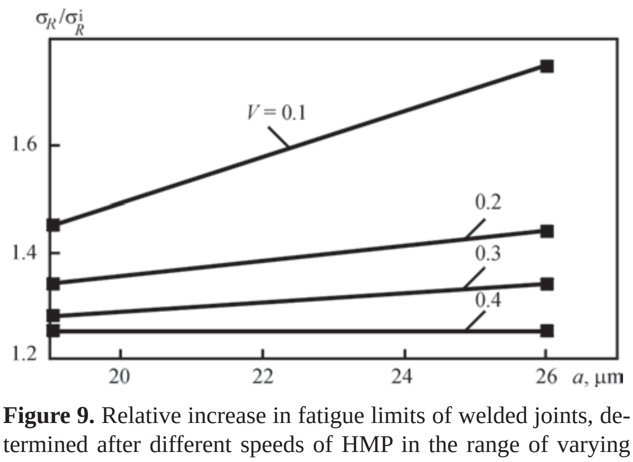

Figure 9. Relative increase in fatigue limits of welded joints, determined after different speeds of HMP in the range of varying amplitude of working tool oscillations of 19–26 μm

where σ_{R1} and σ_{R2} are the fatigue limits of welded joints determined after different speed of HMP at the amplitude of oscillations of working tool $a_1 = 19$ μm and $a_2 = 26$ μm, respectively (Table 3); $\beta = (\sigma_{R_2} - \sigma_{R_1})/(\sigma^{i}_{R}(a_2 - a_1))$ is a coefficient with specific value for each speed of peening; $\sigma^{i}_{R} = 200$ MPa is the fatigue limit of welded joint in the initial state.

From the analysis of results, given in Figure, it follows that both at decrease in the speed of peening and at increase in the amplitude of oscillations of working tool, a more intensive increase in the fatigue limits occurs. The presented data provide a more specific approach to selection of optimal modes of high-frequency mechanical peening at a different combination of its speed and amplitude of oscillations of working tool.

Analysis of results of using mechanical, argon-arc, explosive treatments. The weld zones in specimens of low-alloy steels were subjected to strengthening.

The mechanical treatment (MT) of butt joint of steel 14Kh2GMR produced by manual electric arc welding consisted in removing the weld reinforcement flush with the base metal.

In the argon-arc treatment (AAT) of the butt joint of steel 12GN2MFAYu, which was performed by semiautomatic welding in a carbon dioxide, the zones of weld transition to the base metal were melted by a non-consumable tungsten electrode of 4 mm diameter in argon. The T-joint of steel 15KhSND, made by automatic submerged arc welding, was subjected to explosive treatment (ExT). For this, the cylindrical charges of explosive material of grade DSha-12 were used, laid along the weld on plasticine backings.

Table 3. Calculated values of fatigue limits for butt welded joints, determined after different speed of HMP at different amplitude of working tool oscillations

Speed of HMP, m/min	Fatigue limit σ_R, MPa		$\beta \cdot 10^{-2}$, μm^{-1}
	$a_1 = 19$ μm	$a_2 = 26$ μm	
0.1	290	350	4.29
0.2	269	290	1.79
0.3	255	265	0.714
0.4	250	250	0

The efficiency of methods of strengthening the above-mentioned types of welded joints under different conditions of cyclic loading is shown in Figure 10. In order not to cumber the figures, some fatigue curves are given without experimental points. There, the fatigue curves of specimens in the initial state are also given. The tests of specimens with RS were carried out at $R = 0$, and without RS at $R = 0.5$. This selection was made on the grounds that, as was shown by the earlier investigations [22], at $R = 0.5$ the fatigue limits of welded specimens with high RS and without them have the same values. This allows determining the DLSC of welded joint with high RS according to the results of testing specimens without RS. Analysis of the obtained results showed that fatigue resistance of specimens in the initial state under impact loading is lower than in the case of harmonic loading (curves *1*, *2*). All the treatments increase the fatigue resistance of welded joints both at harmonic as well as at impact loadings in the whole investigated range of fatigue life within the limits of 1.1–1.6 times. From Figure it is also seen that fatigue resistance of treated joints in the conditions of impact loading and –60 °C slightly exceeds their fatigue resistance in the initial state at

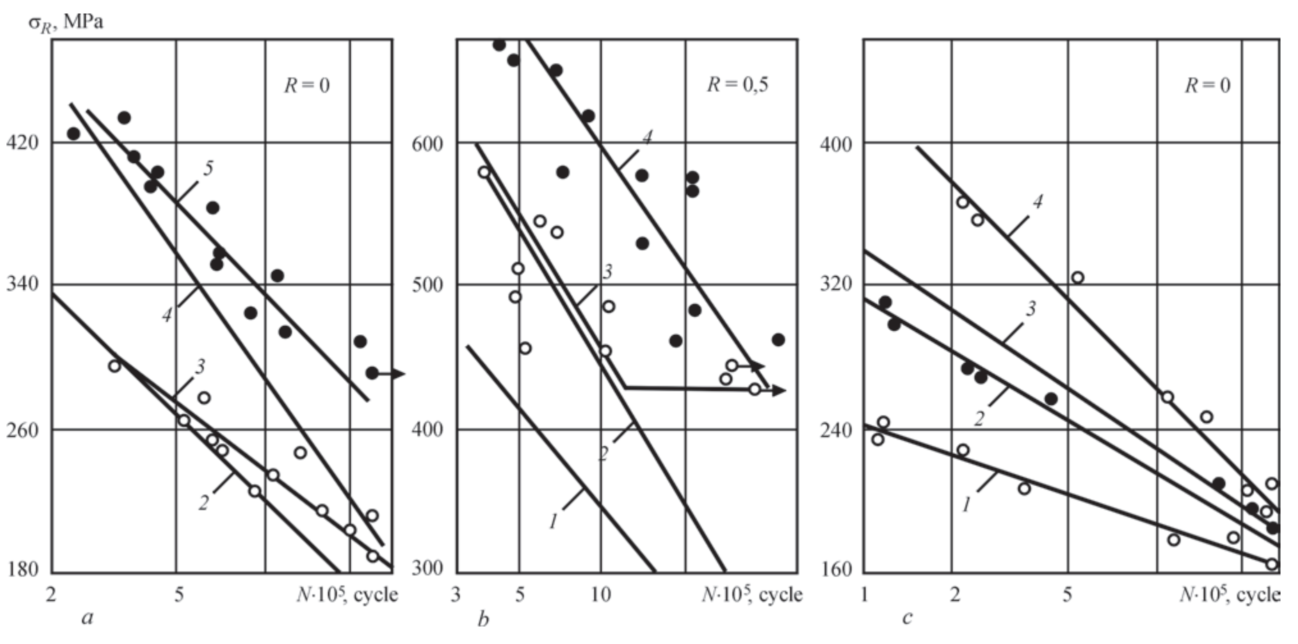

Figure 10. Fatigue curves of butt joints of steels 14Kh2GMR (*a*) after mechanical, 12GN2MFAYu (*b*) after argon-arc treatments, respectively, T-joint 15KhSND (*c*) after explosive treatment: *1*, *3* — impact loading at –60 °C in the initial state and after treatment, respectively; *2*, *4* — harmonic loading at room temperature in the initial state and after treatment, respectively; *5* — at –60 °C

Table 4. Comparative evaluation of effect of type of strengthening treatment on fatigue resistance of welded joints on 10^6 base of loading cycles

Grade of steel, type of joint	Type of weld treatment	Character of loading	T, °C	σ_R, σ_{RO}, MPa	K_{V1}	K_{V2}	K_{V3}
14Kh2GMR, butt	MT MT Without treatment	Impact Harmonic Harmonic	–60 20 20	245 295 225	1.32	–	1.08
12GN2MFAYu, butt	AAT AAT Without treatment Without treatment	Impact Harmonic Harmonic Impact	–60 20 20 –60	451 605 443 335	1.37	1.35	1.02
15KhSND, T-joint	ExT ExT Without treatment Without treatment	Impact Harmonic Harmonic Impact	–60 20 20 –60	235 269 220 187	1.22	1.26	1.07
09G2S, T-joint	HMP Without treatment Without treatment	Impact Harmonic Impact	–60 20 –60	468 398 330	–	1.38	1.18
Steel St.3sp, butt	HMP Without treatment	Harmonic Harmonic	20 20	402 235	1.71	–	–
Steel 20 with welded-on stiffener	VT Without treatment	Harmonic Harmonic	20 20	166 140	1.19	–	–

harmonic loading and room temperature (curves *2*, *3*). This means that the positive effect of strengthening is leveled by negative effect of impact and low temperature, which has a considerable importance for metal structures operated in the conditions of the Extreme North. The explanation of the obtained result is the fact that under the conditions of impact loading and low temperature, the pores existing in welds become dangerous sources of stress concentration, from which the fatigue cracks are developing. This was established during investigations of welded joints of steel 14Kh2GMR with the removed weld reinforcement [23].

To compare the efficiency of methods for strengthening welded specimens, taking into account the different conditions of fatigue test and to give them a quantitative evaluation, a number of coefficients was introduced. The effect of treatment on fatique resistance of welded joints under the conditions of harmonic loading and room temperature was evaluated by the coefficient K_{V1}, and the effect the impact loading and low temperature by K_{V2}

$$K_{V1} = \frac{\sigma_{RO}}{\sigma_R}, \qquad (3)$$

$$K_{V2} = \frac{\sigma'_{RO}}{\sigma'_R}, \qquad (4)$$

where σ_R, σ'_R and σ_{RO}, σ'_{RO} are the limits of limited fatigue of welded joint in the initial state and after additional treatment respectively, whose values at the same fatigue life were determined from the equations of fatigue curves.

The joint effect of treatment, impact loading and low temperature on fatigue resistance of investigated welded joints was evaluated as

$$K_{V3} = \frac{\sigma'_{RO}}{\sigma_R}. \qquad (5)$$

The results of calculations of the coefficients for all types of treatments are presented in Table 4.

It follows from Table that the most effective method of strengthening from the considered ones is HMP, which increases the fatigue resistance of strengthened specimens by 71 %, under the conditions of harmonic loading and room temperature, determined on the base of 10^6 load cycles, and under the conditions of repeated impact and a low temperature it increases the fatigue resistance of the same joint by 18 %, tested in the initial state at the harmonic loading and room temperature. Observing the right treatment technology, this gives grounds to recommend it for strengthening of structures, which operate also in the conditions of cold climate. Regarding VT, the following can be noted. Despite the fact that this method is not distinguished by efficiency of increasing fatigue resistance, however it has an indisputable advantage, which consists in the capability of treating the structural elements with different rigidity in one technological cycle. The analysis of table data showed also that the effect of strengthening almost does not depend on test conditions. This means that fatigue resistance of treated joints under the comparable test conditions is increased approximately in the same way. It can also be noted that the efficiency of the considered treatments according to the coefficient K_{V3} is several times lower than simply under the comparable test conditions, i.e. under the conditions of harmonic loading at room temperature or impact loading at –60 °C. As to the efficiency of strengthening, which is evaluated under the conditions of harmonic loading on the base of 10^6 cycles, the treatments can be arranged in the following sequence: HMP — 71, AAT — 37, MT — 32, ExT — 22, VT — 19 %.

Therefore, on the basis of carried out investigations, it can be concluded that all the considered methods of strengthening treatments increase the fatigue resistance of welded joints, but their efficiency is different and to a great extent depends on the combination of type of cyclic loading and ambient temperature.

Conclusions

1. The procedure for optimizing the selection of vibration treatment modes of welded elements of metal structures of low-carbon steels, which provide an effective reduction of tensile residual stresses without the risk of arising fatigue damages, was tested experimentally.

2. The procedure for determination of fatigue limits of strengthened butt welded joints was suggested applying the technology of high-frequency mechanical peening in the depth of the groove.

3. The efficiency of increasing the fatigue limit of welded joint was determined depending on the high-frequency mechanical peening speed and the amplitude of the working tool oscillations.

4. It was established that the high-frequency mechanical peening is the most effective method of strengthening the investigated welded joints, evaluated according to the criterion of increasing fatigue resistance in different conditions of cyclic loading and ambient temperature. Further the treatments according to their results can be arranged in the following sequence: argon-arc treatment, mechanical dressing of weld reinforcement, explosive treatment, vibration treatment.

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