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METHODS OF EVALUATION OF INCREASE OF FATIGUE RESISTANCE IN BUTT WELDED JOINTS OF LOW-CARBON STEELS AFTER HIGH-FREQUENCY MECHANICAL PEENING

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There was investigated an effect of modes of high-frequency mechanical peening on increase of fatigue resistance of butt welded joints of steel St3sp (killed). Different technology of sample preparation for investigation allowed determining that a quantitative contribution in rise of fatigue limit of welded joints of residual compression stresses, deformation hardening of surface layer of a groove formed after peening of a narrow zone of weld fusion with base metal, and change of stress concentration after high-frequence mechanical peening makes 57, 37 and 6 %, respectively. It is shown that there is a correlation between the groove depth and depth of plastically deformed layer of material. The procedure was proposed for determination of the fatigue limits of butt welded joints after different modes of peening on groove depth and plastically deformed layer of material, using the experimental data of microhardness measurement as well as the change of amplitude of working tool oscillation in the investigated range. A depth of groove was determined depending on rate of high-frequency mechanical peening and amplitude of working tool oscillations as well as change of sample fatigue limit due to different technology of their manufacture. It is shown that increase of peening rate independent on the working tool oscillation amplitude promotes decrease of efficiency of improvement of welded joint fatigue resistance and at 0.4 m/min rate the fatigue limit from deformation hardening and total effect of all factors typical for high-frequency mechanical peening rises by 11 and 26 %, respectively. 14 Ref., 4 Tables, 7 Figures.

Keywords: *welded joint, fatigue limit, groove depth, rate of high-frequency mechanical peening, plastically deformed layer, microhardness*

Intensive development of technological methods for increase of fatigue resistance of welded metal structures and extension of their service life provokes significant attention to high-frequency mechanical peening (HMP) [1–3]. It is related with the fact that it can guarantee considerable rise of fatigue resistance of elements of metal structures and their life [4, 5] in manufacture as well as performance of repair-reconstruction works. It was proposed to use a groove depth [8] forming after peening of a narrow fusion zone of weld to base metal as a criterion of HMP efficiency control instead of rate of movement of working tool along the weld [6, 7]. A value of its optimum depth, equal to 0.14 mm, was determined and the parameters of HMP rate depending on amplitude of working tool oscillations were proposed. However, up to the moment the effect of various peening modes on the welded joint fatigue resistance remains unexplored. Since performance of a complex of full-scale experimental investigations is sufficiently expensive procedure as it takes long time and related with considerable consumption of the material then calculation evaluation of the butt welded joint fatigue resistance in comparison with separate experimental data is the most reasonable solution of the problem.

In this connection aim of the present work lies in calculation evaluation of the effect of HMP modes on increase of the fatigue limit of butt welded joints based on the results of measurement of groove or depth of plastically deformed layer of material under groove bottom using experimental data of microhardness measurement.

Equipment, material and test procedures. Butt welded joint of sheet steel St3sp (killed) made by semi-automatic welding in CO_2 was used as a material for investigation. Various order of preparation of test samples was used to evaluate the effect of HMP modes of welded joints and quantitative contribution into increase of their fatigue resistance of deformation hardening of the groove upper layer as well as residual stresses (RS).

In the first case the separate areas of welded plate of 1000×400 mm size with butt weld was subjected to HMP along weld to base metal fusion line by ultrasonic tool USP-300 [9] with oscillation frequency 22 kHz, deformation mechanism of which presented a 4-striker head with built in it 3 mm diameter rods. Peening was carried out at amplitude of working tool oscillation *a*, equal to 19 μm, and different given rate of its movement *V* (peening rate), equal to 0.232, 0.116 and 0.06 m/min, respectively, which was determined by relationship of length of treated weld to

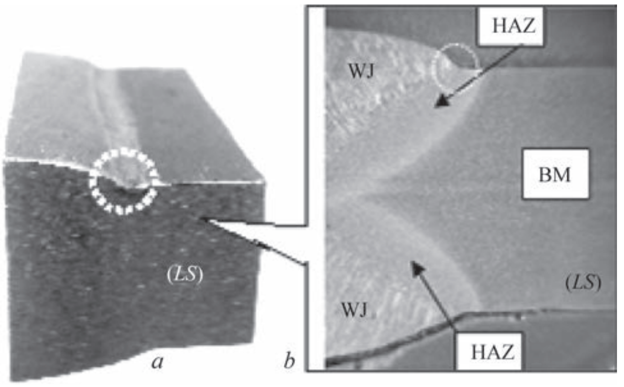

Figure 1. Appearance of template type (*a*), section surface after etching in *LS* plane of cross-section (*b*): *L* — rolling direction; *S* — direction normal to rolling plane; contour outlines groove profile; WJ — welded joint; HAZ — heat-affected zone; BM — base metal

time of treatment. After HMP the groove was formed depending on treatment rate and having 2.8–3.5 mm width and depth *h*, equal to 0.041; 0.062 and 0.143 mm, respectively. After that the plate was cut for samples (series 1) of 40×400×14 mm size with transverse weld, long side of which matched with rolling direction. It allowed considerable reduction of RS available after welding and next HMP of the plate.

In the second case the plate was firstly cut on the samples of the same size (series 2) and then each sample individually was subjected to peening with rate and amplitude of working tool oscillations similar to treatment of the first series samples. The groove of the same size was formed after HMP. As a result, we managed to develop and keep compression residual stresses. Thus, in the samples of the first series the rise of welded joint fatigue limit was caused by presence of hardened layer and decrease of stress concentration coefficient, and in the second by additional effect of compression RS.

It should be noted that identical groove depth can be reached by combination of such parameters as treatment time allowing determining the rate at set width of sample and amplitude of tool oscillations. The paper does not cover the investigation of relationship of depth of the hardened layer and parameters of treatment at similar depth of the groove taking into account that a depth of plastically deformed layer is mainly reflected by microhardness and groove depth. It is proved by methodological investigations of hardening process optimizing carried at PWI [10].

After that one template of 40×40×14 mm size (Figure 1, *a*) was cut from each series of the samples treated at different HMP rate for metallographic examinations.

The metallographic examinations of the samples were performed on optical inverted microscope AXIOVERT 40 MAT. The sections were made on BUEHLER unit in (*S*–*L*) cross-section plane of welded joint normal to sheet rolling direction. Figure 1, *b* shows the surface of the section after etching in 4 % solution of nitric acid in ethyl alcohol. Measurement of microhardness was carried on microhardness meter PMT-3 according to GOST 9450–76 [11] at 1 N loading.

Analysis of obtained results. It is known that HMP results in deformation hardening of the material to some depth from groove surface. It is obvious that different groove depth as well as different depth of plastically deformed layer l_h (depth of hardened layer) will correspond to different modes of treatment. l_h with sufficient level of accuracy can be determined on change of microhardness H_μ.

Measurement of microhardness was carried out in the welded joint cross-section normal to peening direction by parallel rows from the surface of the groove depth inside the material through equal intervals between the rows as well as each row on depth till reaching stable values of microhardness that corresponds to depth of material hardening layer l_h. Figure 2, *a* shows a scheme of microhardness measurement under the groove. Microstructure of heat-affected zone in the area of indentation corresponds to normalizing area (HAZ-2) with uniform fine-grain ferrite-pearlite structure (Figure 2, *b*). Besides, it was determined that different treatment rates were characterized with different maximum depth of hardening layer. It should also be noted that in the samples of the first and second series independent on technology of their manu-

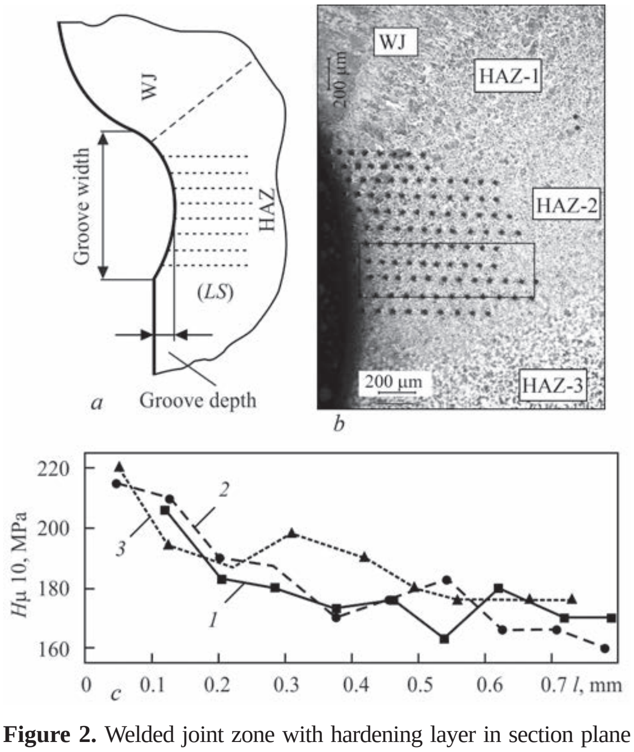

Figure 2. Welded joint zone with hardening layer in section plane (*LS*) after HMP effect with 0.116 m/min rate; *a*, *b* — scheme of measurement of microhardness under groove and microstructure with dents, respectively; *c* — change of microhardness H_μ depending on depth l of material (HAZ-1, HAZ-2, HAZ-3 — areas of coarse grain, normalizing, incomplete resolidification, respectively)

facture the depth of the groove and hardened layer at comparable rates of peening are virtually the same. The similar values of hardened layer can also be explained by the fact that measurements were carried out on side surface of the sample, where effect of RS is virtually absent. Figure 2, *c* as an example shows the results of measurements of microhardness at material depth *l* after HMP of the sample with 0.116 m/min rate. Analysis of ($H_\mu - l$) dependence showed that in each of selected directions there is decrease of microhardness with removal from the surface into material depth. According to the expectations, the maximum depth of hardened layer is reached on the line matching to the maximum groove depth (curve *1*) with gradual decrease at removal from its center. Later on the maximum l_h value will be used in calculations. It should also be noted that the values of microhardness are somewhat decreased with rise of HMP rate. The results of measurements of *h* and l_h in the samples of both series obtained after different rates of HMP are given in Table 1.

It is determined that decrease of peening rate provokes increase of depth of hardening layer and groove with a coefficient of proportionality after processing of the results using least square method being equal to $K = h/l_h = 0.106$. This allows calculating with small error a groove depth being set by any random values of depth of the hardened layer (see Table 1).

Analysis of effect of the hardened layer depth on hardening effect, appearing in rise of welded joint fatigue limit was carried out based on Figure 3. It represents experimentally determined fatigue limits of butt welded joints in the initial state (σ_R^u = 200 MPa) [8] and 0.06 m/min HMP rate in the samples of the first (σ_R = 275 MPa) and second (σ_R = 375 MPa) series at working tool oscillation amplitude a = 19 μm as well as corresponding to them values of depth of the hardened layer. The calculation dependence of welded joint fatigue limit on current depth of hardened layer l_i in this case is the following:

$$\sigma_R^i = \sigma_R^u + Cl_i = \sigma_R^u + \frac{\sigma_R - \sigma_R^u}{l_h} l_i, \qquad (1)$$

where $C = \dfrac{\sigma_R - \sigma_R^u}{l_h}$ is the coefficient of proportionality having its value for each series of samples.

Using the known values of fatigue limits of the welded joint and experimentally determined l_h = = 1.32 mm (see Table 1) it was determined that C = = 56.82 MPa/mm for the samples of the first series and 132.6 MPa for the second. Assumption of proportional increase of the welded joint fatigue limit with rise of depth of the hardening layer, is proved by available references [12]. It should be noted that obtained in the work maximum depth of the hardened layer for the samples of second series is considered as limiting one, since its further rise, first of all, can have no hardening and there is rise of probability of underlayer fracture [12], and secondly, at large stresses it would be impossible to eliminate accumulation of significant cyclic inelastic deformations at the level of fatigue limit that eliminates application of elasticity theory formula [13]. In this case, the fatigue limit, determined at zero-to-compression harmonic stress cycle is considered as a limiting stress.

Table 1. Value of maximum depth of hardened layer and groove in the samples of first and second series, obtained after HMP with different rate

HMP rate, m/min	Depth of hardened layer l_h, mm	Groove depth *h*, mm		Error, %
		Experiment	Calculation	
0.232	0.4	0.041	0.043	4.8
0.116	0.65	0.062	0.069	11
0.06	1.32	0.143	0.14	2.1

Thus, the proposed expression allows in a calculation way evaluating the fatigue limit of butt welded joint (dark points) from deformation hardening and change of stress concentration (line *1*) as well as additional effect of residual compression stresses (line *2*) at any depth of the hardened layer without laboriousness and long-term tests. Besides, the analysis of the obtained results indicates that increases of fatigue limit of the welded samples of the first series made 38 % (line *1*) and maximum increase of fatigue limit of the samples of the second series was 87 % (line *2*). It is easy to determine that portion of effect of compression RS on increment of fatigue limit at 0.06 m/min HMP rate made 57 % and at set in work [14] 14 % reduction of coefficient of stress concentration after HMP the rise of fatigue limit due to deformation hardening of material surface layer made 37 %, decrease of stress concentration was 6 %. However, portion of

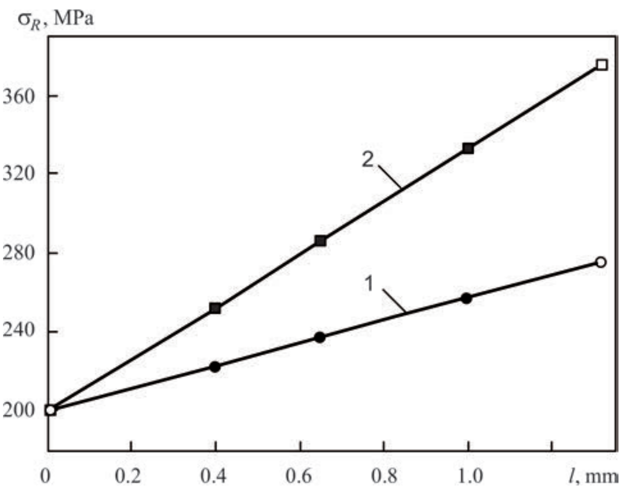

Figure 3. Calculation (dark points) and experimental (white points) depending on fatigue limits of hardened welded joints of the first (*1*) and second (*2*) series on depth of plastically deformed layer

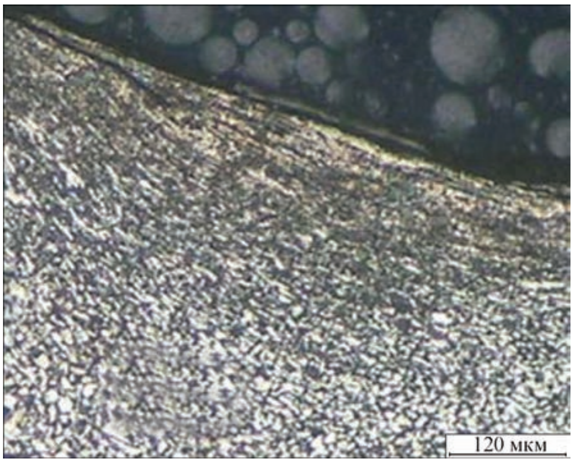

Figure 4. Microstructure of hardened layer under groove bottom in the zone of weld to base metal fusion

each factor requires additional experimental proof. It should be noted that deformation hardening of surface layer of the groove results not only in rise of physico-mechanical properties of the material, but also, as it is shown by metallographic examinations, forming of grains in the hardened layer under its bottom (Figure 4), depth of which depends on peening rate and visually varies in 200–250μm range. This factor can also influence the fatigue resistance of investigated material. However, it order to outline the portion of influence in rise of fatigue resistance of formed after HMP «fiber» structure of the hardened layer it is necessary to set up a special experiment. Thus, increase of the butt welded samples fatigue resistance in the absolute value due to compression RS, deformation hardening and change of stress concentration made 100, 65 and 10 MPa, respectively. Considering small contribution of stress concentration, it can be noted that after HMP the increase of fatigue resistance of the welded joints takes place as a result of influence of compression RS and deformation hardening of the surface layer of groove material.

Since measurement of l_h is related with specific technical difficulties, including presence of necessary equipment, and considering available linear dependence between h and l_h, rise of the fatigue limit after HMP of different rate can be easily calculated on the depth of groove as the simplier controlled parameter. In this case, a coefficient of proportionality, taking into account earlier set dependence ($K = h/l_h$) is determined as $K_1 = (\sigma_R - \sigma_R^u)K/h$. The expression for calculated determination of welded joint fatigue limit will be written as:

$$\sigma_R^i = \sigma_R^u + \frac{(\sigma_R - \sigma_R^u)K}{h}\frac{h_i}{K} = \sigma_R^u + \frac{(\sigma_R - \sigma_R^u)}{h}h_i, \qquad (2)$$

where h_i is the current value of groove depth obtained after HMP of different rate.

Calculation values σ_R^i for each series of samples are given in Table 2. A good matching with the experimentally obtained fatigue limits should not go without mention. It should be noted that the groove depth (h = = 0.14mm) for this thickness of rolled stock is the optimum one [8] and its further rise can have no hardening.

It is known that the groove depth to significant degree depends on amplitude (a) of working tool oscillations. The practice showed that in the most cases the welded elements of metal structures are treated at a varying in 19–26 μm limits. In this connection, using earlier obtained dependencies of the groove depth on HMP rate at 19 and 26 μm amplitudes [8], Figure 5 represents the diagrams, which allow setting the relationship between the depth of groove and peening rate at different amplitude of the working tool oscillations from the one side (Figure 5, *a*) as well as the fatigue limits of welded joints of both series (see Table 2) from other one (Figure 5, *b*), respectively. Analysis of the results presented in such form allows making several conclusions. At set rate of peening it is possible to determine the change of groove depth depending on amplitude of the working tool oscillations (Figure 5, *a*) as well as change of fatigue limit of the welded joints of the first and second series (Figure 5, *b*). It follows from the diagrams (Figure 5, *a*) that rise of treatment rate not only reduces the groove depth, but also effect of working tool oscillation amplitude on its change becomes less obvious since curves 1 and 2 match. This, on the one hand, results in decrease of fatigue resistance of the first (curve *1*) and second (curve *2*) series samples (Figure 5, *b*), and, on the other, influence of working tool oscillation amplitude on its change becomes less effective. At V = 0.4 m/min h has virtually no dependence on a that determines in turn the similar values of welded joint fatigue lim-

Table 2. Dependence of welded joint fatigue limits on depth of groove and corresponding to them HMP rate at different amplitude of working tool oscillations

Depth of hardened layer l_i, mm	Depth of groove h_i, mm	Fatigue limit, MPa		HMP rate, m/min	
		Calculation	Experiment	a = 19 μm	a = 26 μm
0.39	0.041	220*/250	–	0.4	0.4
0.58	0.062	233*/278	–	0.112	0.24
0.94	0.1	254*/325	–	0.075	0.125
1.35	0.143	277*/378	275*/375	0.06	0.09

* — data deal with the samples of first series.

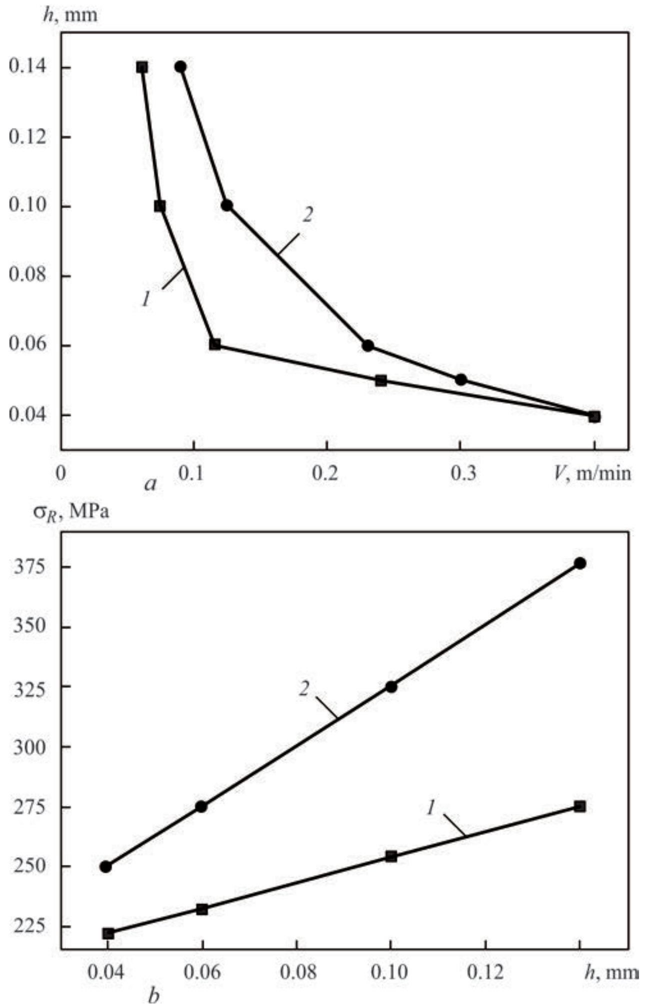

Figure 5. Dependence between groove depth and HMP rate at working tool oscillation amplitude 19 (*1*) and 26 μm (*2*) — *a*, as well as fatigue limits of hardened welded joints of the first (*1*) and second (*2*) series — *b*

it, which for the sample of the first and second series equal to 220 and 250 MPa, respectively. The analysis of the results also showed that rise of h provokes deviation of curves *1* and *2* (Figure 5, *b*). This indicates that the place and order of application of hardening technology in the technological cycle of product manufacture has significant value.

Sometimes at repair-reconstruction works in difficult of access places of the element structures it is not always possible to get reliable determination of groove depth and it is easy to register peening rate. In this connection Figure 6 provides the dependencies of welded joint fatigue limits of both series on peening rate determined at working tool oscillation amplitude 19 and 26 μm, respectively. Analysis of the obtained data shows that in each series the rise of V provokes not only reduction of the fatigue limits, but also decrease of difference between them. It follows from Figure that at $V = 0.4$ m/min the efficiency of increase of welded joint fatigue resistance only due to deformation hardening (curves *1*, *2*) or mutual effect of mentioned factors (curves *3*, *4*) virtually does not

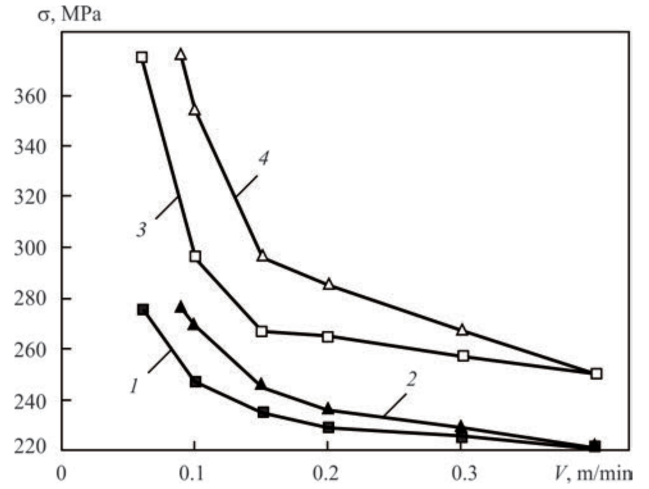

Figure 6. Dependence of fatigue limits of butt welded joints of first (*1*, *2*) and second (*3*, *4*) series on HMP rate in amplitude of working tool oscillations 19 (*1*, *3*) and 26 μm (*2*, *4*)

depend on working tool oscillation amplitude. The fatigue limits have similar values, which by 11 % for the first series of the samples and 26 % for the second one exceed the welded joint fatigue limit in the initial state. Besides, it can be seen that independent on a the rise of peening rate results in insignificant decrease of difference of fatigue limits between both series.

Relative rise of the fatigue limits of the both series of welded joints, determined after HMP of different rate in the range of change of working tool oscillation amplitude from 19 to 26 μm, following from the assumption on proportional increase of fatigue limit, illustrates well the dependencies given in Figure 7. Their calculation values at current oscillation amplitude of working tool a_i can be determined by equation in form of:

$$\frac{\sigma_R^i}{\sigma_R^u} = \frac{\sigma_{R1}}{\sigma_R^u} + \frac{\sigma_{R2} - \sigma_{R1}}{\sigma_R^u (a_2 - a_1)}(a_i - a_1), \qquad (3)$$

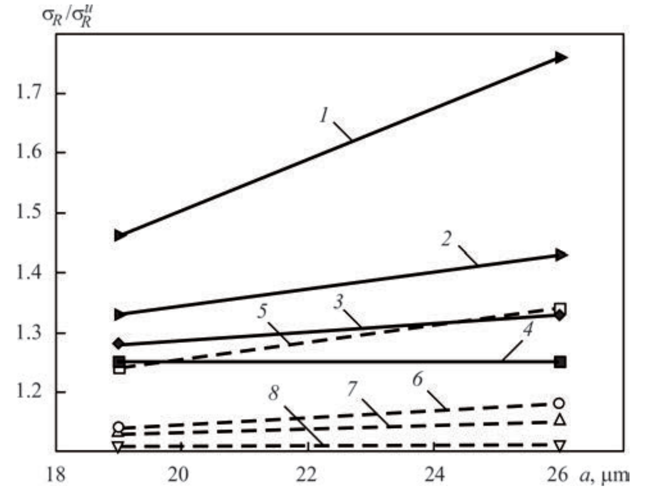

Figure 7. Relative increase of fatigue limits of butt welded joints of first (*5–8*) and second (*1–4*) series, determined after HMP with the different rate in range of change of working tool oscillation amplitude 19–26 μm: *1* — $V = 0.1$; *2* — 0.2; *3* — 0.3; *4* — 0.4; *5* — 0.1; *6* — 0.2; *7* — 0.3; *8* — 0.4

Table 3. Calculation values of fatigue limits of butt welded joints determined at different rates of HMP and amplitudes of working tool oscillations

V, m/min	Fatigue limit σ_R, MPa		$\beta \cdot 10^{-2}$, μm^{-1}
	a_1 = 19 μm	a_2 = 26 μm	
0.1	247*/295	269*/355	1.43*/4.29
0.2	229*/268	235*/290	0.57*/1.79
0.3	225*/255	230*/265	0.286*/0.714
0.4	222*/250	222*/250	0

* — data deal with the samples of first series.

where σ_{R1} and σ_{R2} are the fatigue limits of each series of welded joints determined after different rate HMP at working tool oscillation amplitude a_1 = 19 and a_2 = = 26 μm, respectively (Table 3); $\beta = \frac{\sigma_{R2} - \sigma_{R1}}{\sigma_R^u (a_2 - a_1)}$ is the coefficient having its value for each rate of peening; σ_R^u = 200 MPa is the welded joint fatigue limit in the initial state.

It follows from the Figure analysis that increase of peening rate independent on amplitude of the working tool oscillations provokes decrease of efficiency of rise of the fatigue resistance of welded joint only due to deformation hardening (curves *5–8*) or combination of all factors (curves *1–4*). It should be noted that compression RS are more sensitive to V change since difference between *1–4* curves is more significant at different working tool oscillation amplitude. However, at V = 0.4 m/min the difference between the fatigue limits of samples of the first and second series becomes the same independent on a. It indicates that contribution of compression RS in increase of fatigue resistance of welded joints independent on working tool oscillation amplitude is virtually the same.

It can be seen that at such rate of treatment the effect of only deformation hardening is also the same independent on a. Since reduction of peening rate and increase of the working tool oscillation amplitude provokes more intensive rise of the fatigue limits in the samples of second series, it is possible to make a conclusion that the most effective increase of fatigue resistance can be achieved by application of HMP technology via selection of the corresponding modes of hardening at the last stage of production of metal structure welded elements.

Thus, presented data gave the possibility, first of all, to determine the fatigue limits of butt welded joints after different modes HMP on groove depth or plastically deformed material layer, and secondly, to make more conscious choice of the optimum modes of HMP at various combination of its rate and amplitude of the working tool oscillations considering the technology of manufacture of metal structure elements.

Conclusions

1. The procedure was proposed for determination of fatigue limits of welded joints of low-carbon steel on groove depth and depth of plastically deformed layer of the material under its bottom in the weld to base metal fusion zone.

2. It is shown that there is satisfactory correlation dependence for butt welded joints between the groove depth and depth of plastically deformed layer obtained after different modes of high-frequency mechanical peening.

3. Efficiency of increase of welded joint fatigue limit of different manufacture technology depending on rate of high-frequency mechanical peening and working tool oscillation amplitude was determined.

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