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EFFECT OF VIBROTREATMENT ON FATIGUE RESISTANCE AND DAMPING CAPACITY OF STRUCTURAL ELEMENTS WITH RESIDUAL STRESSES

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A work, based on a complex diagram of cycle limit stresses, proposes a method for selection of vibrotreatment undamaging modes for the elements of metal structures in order to gain effective decrease of their residual stresses without a risk of fatigue damage during technological treatment. This method was approved by the example of testing of the structural elements of steel 20 and end pivot of steel 20GFL of span bolster of eight-axis rail tank car. Comparative fatigue tests showed 2.5 times increase of fatigue life of treated welded specimens and rise of their endurance limit by 40 %. In process of vibrotreatment of a circular element of steel St.3, decrease of residual stresses is accompanied by rise of its damping capacity. Growth of maximum cycle stresses promotes for increase of vibration decrement to larger value and its stabilizing in time matches with residual stress stabilizing. This allows assessing completion of a process of change and further stabilizing of the vibration decrement. Determined decrease of damping capability of the investigated sample after vibrotreatment indicates its strain aging, showing plastic strain during treatment. Rise of cycle stress amplitude reduces sample deformation after vibrotreatment at further aging to 1500 h and decrease of initial residual tensile stresses to 0.51 of yield limit of the material results in its geometry stability. 25 Ref., 2 Tables, 7 Figures.

Keywords: *vibrotreatment, welded joint, residual stresses, endurance limit, cycle stress amplitude, cyclic creep limit, vibration decrement*

Appropriateness and effectiveness of ecological and technological process of vibrotreatment (VT) of welded and cast parts having low consumption of energy and capable to reduce residual tensile stresses (RS) is proved by the world's and domestic experience [4, 5]. These stresses can reduce life of the part [1, 2] or change its shape [3]. Efficiency of the method (treatment time takes not more than 40 min) lies in the fact that cyclic loading of the structure in whole provokes RS decrease in all elements having different rigidity per one technological cycle.

However, a disadvantage of VT is that a value of fluctuating stresses, developed by mechanical vibrators, is selected experimentally. This can result in a stress amplitude, which is insufficient for necessary reduction of RS or such big that can lead to appearance of fatigue damages even at technological stage of treatment [6]. Alongside with indirect methods of VT control, in particular, on variation of current, consumed by vibrator [7, 8], and displacement of resonant peaks on frequency scale [9], there is a method of control on a change of amplitude-frequency characteristic (AFC) [10]. It lies in the fact that width of resonant peak reduces simultaneously with rise of vibration amplitude by VT end. This phenomenon indicates decrease of energy dissipated in the part being treated. A proof is reference data [11] on vibrotreatment of 7000 kg halves of a welded frame of DC machine, which showed reduction of vibration decrement δ from 12.3 to 9 %.

The decrement was determined on width of resonant peaks, recorded before and after VT [12]. However, it is known fact that drop of RS in the metal structure takes place only as a result of plastic strain [13], presence of which should lead to rise of energy dissipated in the material [12]. Obvious contradiction in a direction of change of material vibration decrement to observed in practice vibration decrement of the part can be explained by the fact that located on the floor being treated parts together with energy dissipation in the material have also structural dissipation of energy, change of which is mainly reflected in AFC. This assumption is proved, first of all, by large absolute values of δ at VT of the specimen simulating structure of cast-iron frame of cutting machine (8.3 %) [14], and shells of titanium with welded stiffening ribs as well as steel shaft (4.0 and 3.5 %, respectively) [15]. Secondly, change of vibration decrement of the part in VT process, for example, in frame of DC machine by 3.3 % as well as in two welded bodies of coordinate measuring machines [11] by 4.2 and 2.8 %, respectively, somewhat exceeds absolute the value of the vibration decrement of material, which at stress, typical for VT and under room temperature conditions, makes 0.2–1.0 % for carbon steels, 0.05–0.15 % for titanium alloys and 2–5 % for cast iron [16].

Thus, existing up to now contradiction on direction of change of the material vibration decrement to one observed under industrial conditions, first of all, indicates weakness of control of VT process on criterion, which is based on determination of integral characteristic of energy dissipation in the structure, change of which in the process of VT, firstly, is not related with change of residual stresses and, secondly, many times exceeds energy dissipation in the material. Since RS change takes place in the material of part being treated, then this process should be evaluated on variation of energy dissipation in the material.

In this connection, aim of the present paper lies in optimizing the VT method for the elements of metal structures and evaluation of its effect on their fatigue resistance and determination of interconnection of change of energy dissipation in the element being treated with residual stress kinetics.

Research objects, testing equipment. Research on VT method optimizing was carried out under laboratory conditions on specimens of steel 20 (σ_t = = 440 MPa, σ_y = 290 MPa) of 100×400×420 mm size with a rib welded-up along the long side of the specimen as well as under industrial conditions. Welding-up of the rib by semi-automatic CO_2 welding with the specimen immersed to the middle in water allowed developing high residual tensile stresses. Their value and sign, matching with loading application direction, were determined by magnetic noise method, based on application of Barkhausen effect [17]. RS distribution diagram showed that they are maximum at weld to base metal interface and made on average 220 MPa, i.e. $0.76\sigma_y$, and at 12 mm distance they equal zero and then transform to compression ones. Value of the maximum residual tensile stress σ^i_{res} was further used in analysis of RS kinetics. Under industrial conditions VT was carried out for box-section bolsters (hereinafter bolsters) of 190×170×2000 mm size and zones of welding-up of end pivot to the elements of span bolster of eight-axis rail tank car of steel 09G2S. The pivots of complex configuration are made by electroslag casting of steel 20GFL (σ_t = 740 MPa, σ_y = = 590 MPa) and bolsters were produced by welding of 20 mm thick sheet steel 20. Necessity of VT of the end pivot is explained by its frequent fatigue fracture in operation.

VT of the metal structures was carried out using electromechanic vibrator IV107 by means of development of fluctuating loads of resonant or near-resonant frequencies as well as applying pulsator TsDM-200pu in a forced vibration mode allowing tests at any cycle asymmetry. Stress amplitude was measured by a strain-gage method.

Bending fatigue tests of the specimens were carried out on DSO-2 [18] machine at set coefficient of stress cycle asymmetry R under conditions of harmonic loading at 20 Hz frequency. Stress amplitude was measured by strain-gage method.

Investigation of change of energy dissipation in the material was performed using the specimens cut out from as-delivered St.3 steel pipe of 275 mm diameter and 8 mm thickness. Mechanical characteristics in tension of cylinder specimens, cut out from a pipe wall in tangential direction, made $\sigma_{0.2}$ = 235 MPa, σ_t = = 450 MPa. Circular specimen of 115 mm width with a cut was fixed in its upper part to vibration node by means of screw clamp, which in turn was stringed. Due to such scheme of fixing, there is no possibility of structural damping. A principle of resonant excitation of bending vibrations of the specimen is realized in the machine via electromagnets, fastened to its edges. Cyclic stresses were developed due to periodic approaching and removal of ends of the specimen and were calculated on deformation of strain gage, glued in the area of maximum bending moment effect. To develop RS on the outer surface, the specimen was deposited in the middle of circumference and its internal surface was cooled by running water. Evaluation of value and sign of RS in a near-weld zone, acting along the deposit, was carried out by magnetic noise method [17]. Values of σ^i_{res} at 2 mm distance from the deposit made on average 200 MPa, i.e. $0.85\sigma_{0.2}$, and at 8 mm distance it was 50 MPa. A vibration decrement was determined by recoding a vibrogram of free damped vibrations of the specimen [19] using for this indicated strain gage. Due to the fact that the deposit can damage a probe, determination of δ was duplicated applying one more method. Industrial TV unit PTU-61 was used to measure vibration span of the specimen. The TV camera in order to increase measurement accuracy was attached to MBS-1 microscope fixed on test machine body. A frequency meter was used for measurement of number of cycles of specimen vibration, corresponding to half damping of their span. The vibration decrement was determined at σ_a = 7 MPa cycle stress amplitude. The minimum σ_a in VT made 15 and maximum one was 60 MPa.

Analysis of research results. Optimizing of the VT method lied in selection of undamaging modes of loading of metal structures for reduction in them of RS without a risk of fatigue damage. It is based on application of complex diagram of cycle limit stresses (DCLS) (Smith diagram) (Figure 1). A line of limit stresses 1 was determined with respect to received endurance σ_R limits of the specimens with welded-up

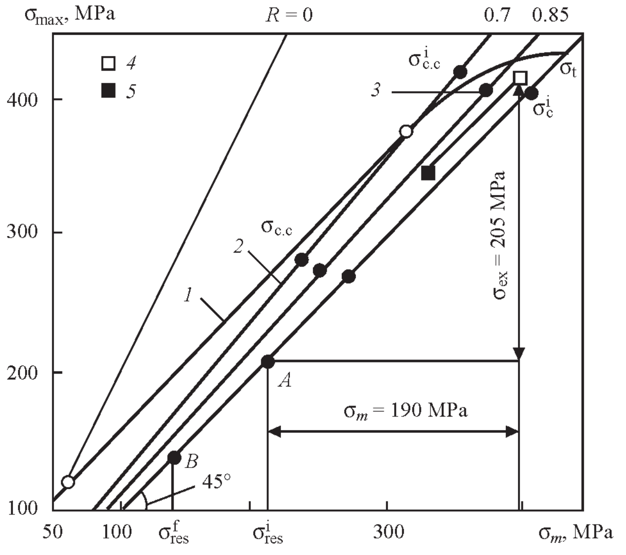

Figure 1. Diagram of limit stresses of steel 20 welded joint (*1*), lines of cyclic creep limits of material in tension (*2*) and bending (*3*), total stresses is in initial state (*4*) and after 10^5 cycles of loading (*5*)

rib of steel 20 on the basis of $2\cdot10^6$ cycles of loading at $R = 0$ and 0.7. It is limited by endurance limit at symmetric cycle of loading (not indicated in the Figure) and strength limit σ_t. Lines *2* and *3* correspond to experimentally determined limits of cyclic creep $\sigma_{c.c.R}$ [20] of steel 20 at tension and bend, obtained at $R = 0.7$ and 0.85, i.e. maximum stresses, under effect of which a set value of residual strain ε_{cr} is reached for given test basis in cyclic creep mode. In this case $\varepsilon_{cr} = 0.2$ %. They are limited by creep limit at static loading (σ_y is allowed) and endurance limit, called the minimum cyclic creep limit $\sigma_{c.c}$. Since specimen tests were carried out at bending, then DCLS section received under the same conditions was used for setting the stresses from external loading σ_{ex}. Before VT, an initial maximum residual stress σ^i_{res}, varying in each

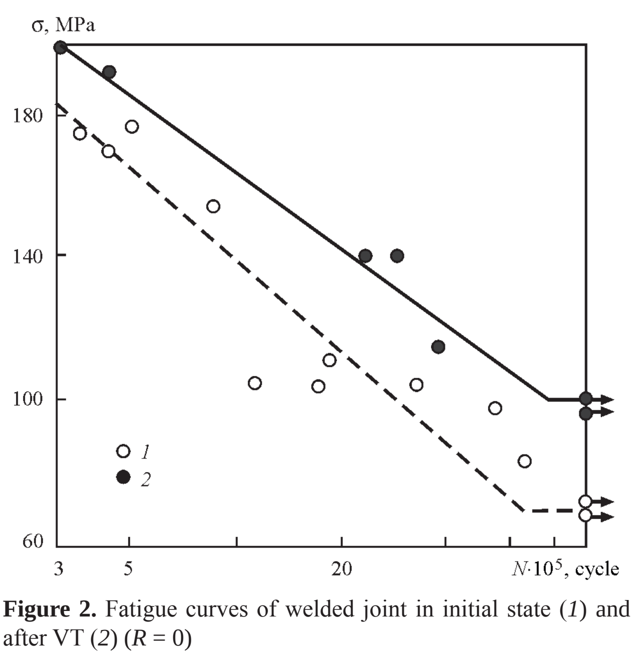

Figure 2. Fatigue curves of welded joint in initial state (*1*) and after VT (*2*) ($R = 0$)

specimen in 210–220 MPa range, was plotted on diagram (t. *A*). Stress from external load, which should be applied to the specimen, was determined following the condition

$$\sigma_{c.cR} < \sigma_{ex} + \sigma^i_{res} < \sigma_R,$$

where σ_R, $\sigma_{c.cR}$ are the stresses corresponding to intersection of effect of cyclic stresses with limit stresses lines *1* and *3*, respectively. Condition $\sigma_{ex} + \sigma^i_{res} << \sigma_R$ provides for absence of fatigue damage after VT, and $\sigma_{c.cR} < \sigma_{ex} + \sigma^i_{res}$ is the efficient reduction of RS. According to procedure, σ_{ex} is calculated in such a way that the maximum stresses locate below line *1*, but above line *3*, that guarantees absence of fatigue damages and effective decrease of RS. If σ^i_{res} was more than the average stress of respective $\sigma_{c.c}$, then application of symmetric cyclic load is enough for RS reduction. Since it absent in this case, then for RS decrease it is necessary to apply asymmetric loading, staying in a safe area of loading. $\sigma^i_{res} = 215$ MPa value was used for calculation of parameters of external load (their values are presented in Figure and in Table1). VT duration made 10^5 cycles of loading. The loading modes were kept stable during this time. It can be seen that VT provoked reduction for more than 40 % (darkened square in Figure) and it made on average $0.45\sigma_y$ of steel 20 (t. *B*). Comparative fatigue tests were carried out for evaluation of effect of low RS. Analysis of obtained results at zero loading cycle under room temperature conditions (Figure 2) indicates increase of endurance of the vibrotreated specimens in the whole range of applied stresses (curve *2*). For comparison, the Figure shows fatigue curve 1 of the specimens with high RS, received in initial state. It can be seen that load fall provides for rise of their effect due to what fatigue curves separate. For example, endurance of the vibrotreated specimens increases from 1.5 to 2.7 times at decrease of stresses from 180 MPa to endurance limit stress level, equal 100 MPa. At that, endurance limit determined on the base of $5\cdot10^6$ cycles of loading grew by 40 %. VT of the bolsters and pivots was carried out by means of electromechanical vibrator IV107 at near-resonant frequency for around 20 min that corresponded to 10^5 cycles of loading. Decrease of residual stresses to σ^f_{res} was judged on measurement of current, used by vibrator. Stress amplitudes were determined based on condition mentioned above, and $\sigma_{c.cR}$ value at $\varepsilon_{cr} = 0.2$ %. The results of testing are given in Table 1. Analysis of the results showed that VT technology at maximum reached amplitude of stresses σ_a allowed decreasing initial RS by 20–22 %, which on average made $0.65\sigma_y$ of respective steel. In some bolsters RS were of such level that their reduction required a stress amplitude exceeding

Table 1. Results of reduction of maximum residual tensile stresses depending on type of equipment used in VT

Research objects	Equipment	Values of stresses at undamaging modes of vibrotreatment for RS decrease in welded structures, MPa							
		σ^i_{res}	σ_R	$\sigma_{c.cR}$	σ_{ex}		σ_{max}	σ^f_{res}	$\sigma^f_{res}/\sigma^i_{res}$, %
					Amplitude	Static			
Bolster	Vibrator	245	290	275	40	0	285	190	78
	Pulsator	230	330	265	20	70	320	155	67
		230	330	265	22	70	322	150	65
		200	320	265	28	88	316	145	72
		175	315	265	24	109	308	120	69
Pivot	Vibrator	480	530	515	35	0	515	385	80
Specimen	DSO-2	215	430	405	15	190	420	125	58
Bolster	Heat treatment	240	–	–	–	–	–	100	42
Pivot	Same	480	–	–	–	–	–	210	44

line *1* (see Figure 1). In this cases TsDM-200pu pulsator was used for asymmetric cyclic loading in a mode of forced vibrations of 10 Hz frequency. Asymmetric loading allows significant expansion of VT capability due to increase of stresses from external load, values of which are given in Table 1, keeping them in the safe area. It can be seen that in this case vibrotreatment decreased initial RS on average by 32 %, which made $0.5\sigma_y$. For comparison, let's note that RS values in the bolsters and pivots after heat treatment made on average $0.35\sigma_y$.

Thus, carried tests showed that VT can compete with annealing in increase of endurance and fatigue resistance of non-critical structures, in particular, if consider high cost and duration of annealing technological cycle.

Effect of amplitude of cycle stresses and time of RS change in the circular specimens and their vibration decrement was also investigated at VT. Design of the specimen and scheme of its loading allowed determining variation of vibration decrement in the material as well as its geometry stability. The diagrams of RS distribution on the specimen width at different number of loading cycles showed that the maximum RS have the most intensive reduction, and at 6 mm distance from the weld, where initial RS equal approximately $0.5\sigma_{0.2}$, their change was not observed. The results of relative change of decrement and maximum RS are given in Figure 3, where the δ^i and δ^i_{res} are vibration decrement and residual stress in initial state, and δ, σ_{res} are their current values in process of VT. Table 2 shows values of δ^i at σ_a = 7 MPa and σ^i_{res} for each tested specimen.

Obtained results indicate that cyclic loading of the specimens promotes simultaneous decrease of RS and rise of vibration decrement that can be a consequence of material plastic strain [12]. Plastic strain in the specimens is proved by the data on relative change of vibration decrement δ/δ^f in course of time after VT of the specimens at different maximum cycle stresses

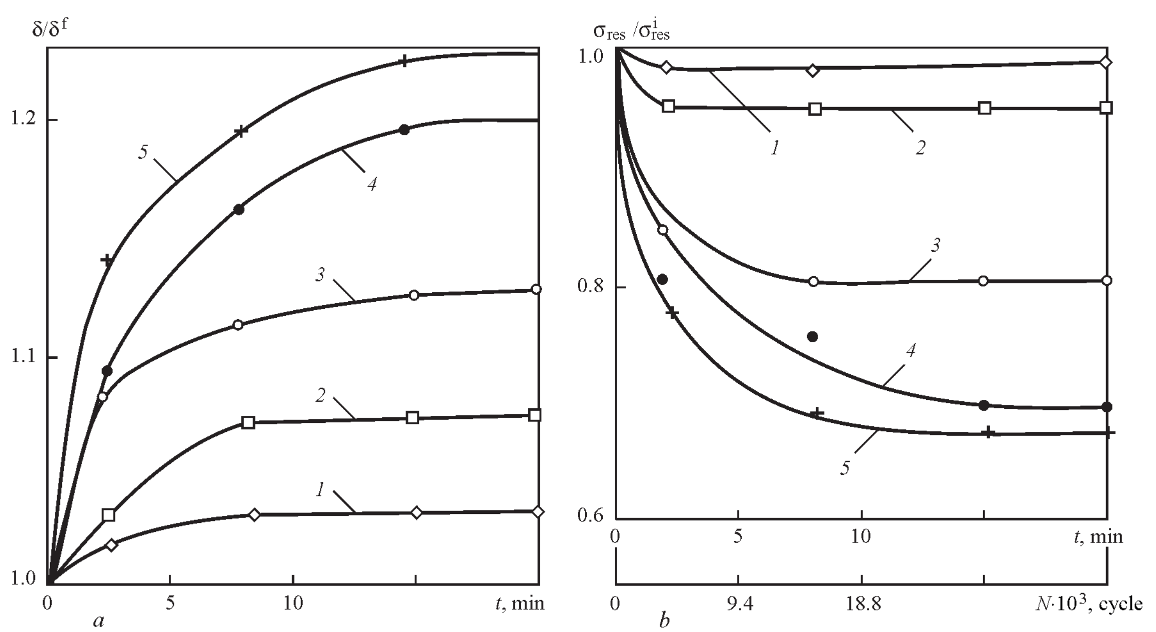

Figure 3. Dependence of relative change of vibration decrement (*a*) and maximum residual stress (*b*) on VT time at different maximum cycle stresses σ_{max}: *1* — 185 MPa (σ_a = 15 MPa); *2* — 205 MPa (15 MPa); *3* — 230 MPa (50 MPa); *4* — 235 MPa (30 МПа); *5* — 265 MPa (60 MPa)

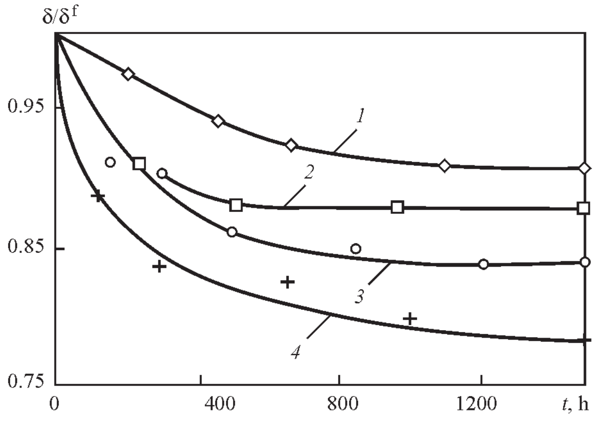

Figure 4. Relative change of vibration decrement in course of time after VT of specimens at different maximum cycle stresses σ_{max}: *1* — 185 MPa (σ_a = 15 MPa); *2* — 205 MPa (15 MPa); *3* — 230 MPa (50 MPa); *4* — 265 MPa (60 MPa)

(Figure 4), where δ is the current decrement value, δ^f is the final value of decrement after VT end (determined using the curves given in Figure 3). Presented graphs (Figure 4) show that the vibration decrement drops in all specimens in course of time, that indicates passing of process of strain aging in the material of specimens after VT. It appears only as a result of plastic strain of material [21]. The larger value of decrement at VT, the lower is its decrease in time. In 1000–1500 h its value was virtually stabilized depending on maximum cycle stresses.

Effect of static stresses on vibration decrement of the specimens [16] is known. Similar effect of residual stresses can be expected. Reference data [22] were used for evaluation of decrement change only due to residual stress decrease. It is shown that change of static constituent from 150 to 100 MPa at amplitude of bending stresses 60 MPa in the specimens of low-carbon steel results in a relative rise of vibration decrement approximately by 3 %. The results of test-

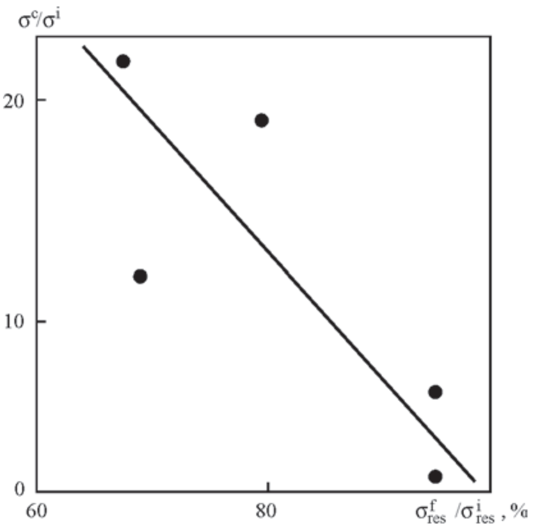

Figure 5. Dependence of relative change of vibration decrement δ^f on relative change of residual stress σ^f_{res} determined at the end of VT at different modes of cyclic load

Table 2. Initial values of vibration decrement of material and maximum residual tensile stress

Specimen number	σ^i_{res}, MPa	δ^f, %
1	170	0.107
2	180	0.112
3	190	0.12
4	205	0.111
5	205	0.13

ing of the specimens of steel 45 [23] at all did not show decrement change in reduction of static stress from 250 to 150 MPa. Relative increase of δ of circular specimen at the same stress amplitude at the end of VT made 1.22, i.e. 22 % (see Figure 3). It is obvious that the main reason of change of vibration decrement of the circular specimens material was their plastic strain at cyclic loading. Measurements of RS in the specimens at different intervals of time after VT did not show their changing. Increase of maximum cycle stresses, equal $\sigma_{max} = \sigma^i_{res} + \sigma_a$, promotes the highest rise of the vibration decrement and decrease of RS (see Figure 3). The most intensive decrease of RS and increase of δ is observed in course of 5–10 min, that corresponds to $(9.4–18.8)\cdot10^3$ cycles of loading. Moreover, the lower the maximum stress, the smaller is the time of stabilization processes in the specimen. Further rise of VT time has virtually no effect on RS and δ. Analysis of the reference data [24] also verifies obtained result on effect of number of loading cycles on RS decrease at VT. It is also necessary to take into attention that stabilizing of the vibration decrement and RS on number of cycles virtually matches. Therefore, change and further stabilizing of δ can be used for judging the process of reduction and further stabilizing of RS in the part being treated, and, respectively, time necessary for its VT. Since, according to data of the Figure, stress amplitudes from 15 MPa and more provokes change and further stabilizing of the processes taking place in the specimen material, then, apparently, only nature of δ change without its numerical value can not be used for evaluation of VT efficiency from point of view of quantitative reduction of residual stresses.

Quantitative relationship of relative change of the vibration decrement and RS, determined in 20 minutes of VT of the specimens with different stress amplitude is given in Figure 5, where the final values of vibration decrement and RS are determined on data of Figure 3. Reduction of RS was observed, regardless the fact that maximum cycle stresses at VT of the most specimens were lower than the yield limit. VT at the most intensive in the experiment mode of loading (σ_a = 60 MPa) resulted in relative increase of the

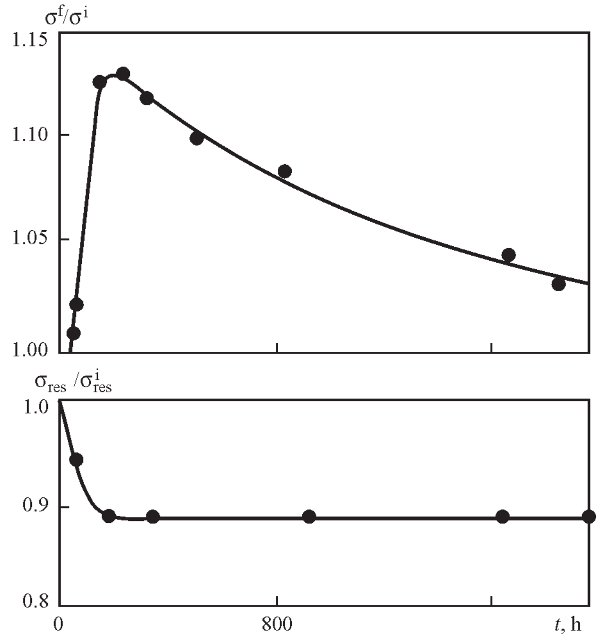

Figure 6. Dependence of relative change of vibration decrement and maximum RS on time in specimen without VT

vibration decrement by 22 % and reduced initial RS (205 MPa) by 32 %. In an absolute value, rise of the vibration decrement of the material $\Delta\delta = \delta^f - \delta^i$ only for 0.024 % corresponds to decrease of initial RS by 65 MPa. Such a graph can be useful for determination of the optimum mode of VT. Obtained experimental results showed that evaluation of efficiency of VT on criteria of total energy dissipation in the structure at such a small value of vibration decrement of the material and, its far lower change in process of RS reduction in the material, is impossible without consideration of structural energy dissipation.

In order to evaluation VT efficiency the observations were directed on relative change of the vibration decrement and RS in the specimen in a different time periods after making a longitudinal deposit under condition that the specimen was not subjected to VT. Analysis of the results, given in Figure 6, showed that δ rises and RS decrease up to 150 h similar to the specimens subjected to VT. Moreover, stabilizing moment of the studied characteristics matches in time. Then as a result of strain aging the vibration decrement drops virtually to initial value, and RS remain unchanged. Decrease of δ indicates that even in absence of VT an effect of high RS provokes plastic strain in the specimen, that results in reduction of initial RS. Comparing the experimental data in Figures 3 and 6 it can be noted that stabilizing process at natural aging takes place after a longer period of time (in this case in 150 h), regardless the similar nature of change of the vibration decrement and RS. It can be practically concluded that VT significantly accelerates (450 times) the process of RS decrease in the welded structures. Therefore, in earlier works [25] term «vibrotreatment» was used as «vibroaging».

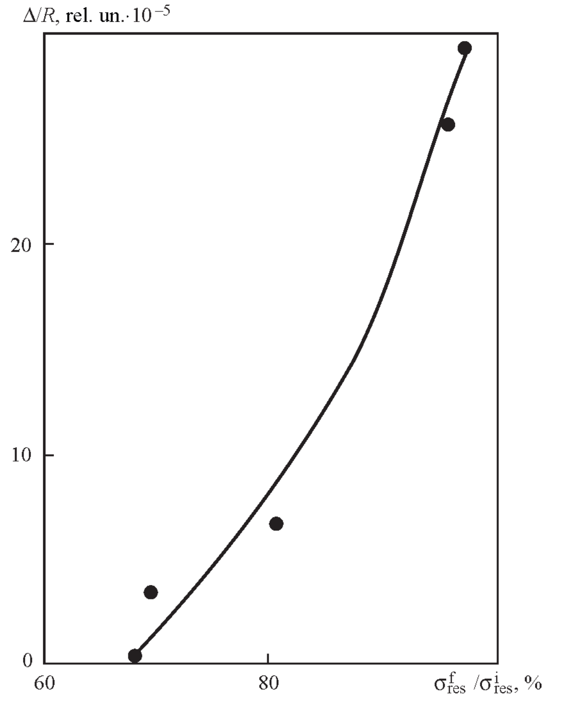

Figure 7. Dependence of change of relative gap in circular specimens on relative change of RS determined in 1500 h of aging after vibrotreatment at different amplitude of cycle stress (σ_a =15, 15, 30, 50, 60 MPa). *R* — circular element radius

One of the VT tasks includes also prevention of buckling of structure elements in storage and operation, therefore this work also studies effect of stress amplitude on change of a linear size of the circular specimens, which was expressed in a change of gap Δ between its free ends during VT as well as after it. Received results showed that gap decrease mainly takes place in course of $7.5\cdot10^3$ cycles of loading and after $15\cdot10^3$ cycles of loading it does not change independent on σ_a value (not indicated in Figure). Also it can be noted that increase of applied amplitude σ_a provides for reduction of the value of further after VT buckling of the specimen and at σ_a = 60 MPa change of the gap in process of specimen aging in course of 1500 h was not observed. A dependence, presented in Figure 7, gives an evaluation of change of the relative gap in the circular specimens due to relative change of RS, determined in 1500 h after VT. Smaller change of the gap after VT corresponds to larger value of residual stress decrease. It is determined that decrease of initial RS by 32 % that corresponds to 0.51 $\sigma_{0.2}$ of the investigated material did not provoke change of the specimen gap. The resu~lts of testing showed an appropriate level of RS reduction in this case in order to reach geometry stability of the investigated element.

Conclusions

1. The method for selection of the undamaging modes of vibrotreatment of the welded elements of metal structures was developed and experimentally tested based on a complex diagram of cycle limit stresses. They provide for efficient decrease of residual stresses and increase of endurance limits.

2. It is determined that reduction of residual stresses in vibrotreatment results in increase of damping capability of the part material. Growth of the maximum cycle stresses provokes increase of vibration decrement on larger value, and its stabilizing and stabilizing of residual stress match in time. This allows making a conclusion about process end on beginning of vibration decrement stabilizing.

3. Decrease of vibration decrement after VT indicates the process of strain aging pointing plastic strain of the specimens in vibrotreatment. This results in decrease of residual stresses.

4. Vibrotreatment can also provide geometry stability of the welded elements. It is determined that decrease of initial maximum residual tensile stresses to 0.51 of material yield limit results in geometry stability of the circular specimen.

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