The Tools, Technology and Mathematical Model of Impactive Superficial Plastic Deformation of Metals

Dr., prof. S. Shestakov[1], Dr., prof. E. Smeshek[2]

[1] Moscow state university of Technologies and Management,
Russian Acoustical Society, Russia,
[2] Polessky state university, Republic of Belarus

Abstract

The paper shows scientific substantiation and practical confirmation of possibility, application expediency and efficiency of the ultrasonic superficial plastic deformation in zones of welded connections after performance of welding works. For this purpose, a mathematical model to the process of superficial plastic deformation is represented, as the hypercycle of loading consisting of elementary cycles – impacts. we described the standard measurement devices. The technology is intended to use the manufacturing and repair of any metal walls in places of dimensional and structural nonuniformity, such as mechanical defects or a local thinning of a surface owing to corrosion, and the microcracks. The microcracks is influenced by the external forces and become zones of concentration of mechanical tension. Hardening in such places of the pipes walls and tanks working under pressure is effective for pipelines of an oil and gas, water supply systems, and also for caissons and tanks of other appointment. The scopes of technology include the repair of river and sea vessels, objects of oil production. The technology can be applied to improvement of operational characteristics of mechanical engineering and transport details, objects of energetic and construction: surfaces of a rolling motion and sliding of machines and devices, wheels of a rolling stock of railway transport, a metalwork of support of power lines, platforms and bridges for increases in resistance of fatigue at cyclic loadings, wear resistance and corrosion.

Keywords: Impactive superficial plastic deformation – a peening, the tension-deformed conditions, ultrasonic impaction tool, ultrasonic peening, welding connection, welding.

1. Introduction

The technology of impactive processing of welded seams, zone of mechanical postwelding tension and the designs of ultrasonic tools for its realization, are widely described in scientific and technical literature and the last century patents [1-5]. However, they were most deeply investigated only by 1997 at repair of the main gas pipeline "Gryazovets-Leningrad" [6]. A bit later, the mechanic-mathematical model to the process was formalized and transformed into algorithms and computer programs [7].This technology belongs to the ways of cold processing. It is classified as a way of a peening – hardening of materials according to their impactive superficial plastic deformation by the instrument of vibration action. It was established and scientifically proved that it may be carried out in the best way by tool with a source of mechanical energy in the form of the resonator of elastic fluctuations of ultrasonic frequency, which transfers impaction impulses by the free elements –"impact hinges" [6].This technology belongs to the ways of cold processing and is classified as a way of a peening – hardening of materials to their impactive superficial plastic deformation by the instrument of vibrational action. Scientifically are was proved that it may be carried out in the best way by tool with a source of mechanical energy in the form of the resonator of elastic fluctuations of ultrasonic frequency, which transfers impaction impulses by the free elements – by "impact hinges" [6]. As earlier the technology was investigated with reference to repair of the pipe of main gas pipelines, this article opens the features of ultrasonic peening process, its difference from analogs and considers tasks which decide by means of her at performance of welded connections on pipes. The main feature of this application is that the pipe of the gas pipeline is a vessel working under internal pressure, which generates in the welded seams the mechanical tension of the same sign, as the residual tension arising after welding at cooling of welded seam and metal near it. Therefore on the gas pipeline the problem of corrosion protection of places of welding is very important [8-10]. On welded connections in general operational loadings can be with another sign, including the tension with a variable sign that according to Bauschinger's effect can weaken them even more. Therefore the problem of corrosion continues to be important, but the problem of hardening remains significant. The theory of this technology includes the theory of mechanical blow, deformation of solid body and the theory of the nonlinear phenomena in mechanics of elastic fluctuations. According to the general ideas of mathematical models of metals deformation by pressure or by blow, they are based on such sections of applied mathematics and the system analysis, as theory of functions of the complex variable, theory of similarity and numerical methods of the analysis. In the field of technological application of ultrasonic fluctuations for processing the solid body, two scientific directions are theoretically enough fully developed. The theory of ultrasonic processing is developed in the works [11-13], where the ultrasonic converter is equipped with tools for transformation of fluctuations and transfer their

energy to processed object, is considered directly as a source of technological influence. The second direction, characterized in works [14-16], considers ultrasonic fluctuations as an auxiliary factor of influence in traditional technology of processing by pressure. The discussed in this article the technology is located between these representations. In they mechanical influence is transferred to processed object via elements (impact hinges) which rigidly mechanically not connected neither with a source of fluctuations, nor with an object of processing. That is periodic mechanical contact with a double break, but the arrangement of a source of force in the kinematical scheme isn't limited to the motionless situation how in [17]. It should be noted that level of a problem here still remains phenomenological, based on empirical data. And operative control of processing (metrological task) obviously lags behind achievements in the field of technology and of equipment of impactive ultrasonic processing.

2. Review of Special Literature
2.1 Concerning Technology and Control Methods

In patent and technical literature numerous ways of superficial plastic deformation of details of mechanical engineering [18-20] including the tool with use of ultrasonic fluctuations [21-24] are described. All they don't envision any special methods of control of the hardening. Therefore at their use is impossible precisely to establish during processing object how more strongly he will resist to operational loadings. Besides, the compressing tangential tension created at plastic deformation and absence of control of peening, especially on thin-walled objects, can spontaneously relax, causing deformations in the form of corrugations. Application for control of processing of methods of a tensometry, such as a method of magnetic memory, a method of acoustic emission [25] or a method based on the phenomenon of an acoustic elasticity of [26,27] for measurement of removal by superficial plastic deformation of postwelding mechanical tension in an welded connections is almost impossible. Each of these methods demands use of a complex of difficult in service the devices and special skills of the personnel that strongly complicates work of they especially in field conditions and in hard-to-reach places. At such works and without that is required supervised quality of the welding on defects, as in [28] where make ultrasonic processing of places of tea leaves of corrosion defects of a pipe. In work [29] where advantages of this way are described, charts of tangential tension are constructed on the results of laboratory researches, obviously, with application of the mentioned method of magnetic memory as their size is expressed in terms of intensity of a magnetic field.

In [30,31] is described, how control is carry out in the first case on duration of processing and in the second, besides, supervise sizes of a blows impulses, using sizes of developed efforts and initial hardness of metal of processed object. What is concerning processed object supervise only initial characteristics. Control of the current sizes is carry out only concerning the parameters defining dynamics of blow, and the general duration of the processing. Thus it is impossible to define extent of hardening even indirectly, and direct measurement of a peening on residual tension again will need application of one of types of a tensometry: electric, magnetic, x-ray or acoustic.Similar shortcoming has and technological complex for the processing of welded objects [32] in which in operating time supervise amplitude of fluctuations of a source of mechanical energy and similar to it ways of superficial plastic deformation under the influence of ultrasonic fluctuations [33,34] in the course of which supervise the noise level from impacting elements. It gives the chance to provide optimum parameters of process of processing, but doesn't allow to define a peening from plastic deformation and measure a residual tension, and also to compare received hardening to the desirable. Indirectly at implementation of ultrasonic impactive processing for the hardening its can be supervised by the quantity of blows, amplitude of ultrasonic fluctuations, force of a static compression and speed of moving of the tool, knowing number, a form and the size of impact elements [35]. Criterion by means of which carry out control of impactive plastic deformation is made of these parameters.

At strengthening and passivating of the walls of pipelines of the high pressure struck with corrosion which was made in 1997 during repair of the gas pipeline "Gryazovets-Leningrad" in criterion also were included the change of frequency of blows and size of residual deformation. Measurement of the last parameter demanded alternation of processing with measurements of thickness of a wall. Thus was created is a repeated-periodic mode of processing and measurements. Unlike the intensity of the noise supervised in examples considered above, frequency of blows at repeated-periodic processing bears information about change of factor of restoration at elastic and plastic blow [36]. By the change of frequency of blows if is known a rebound distance of the center of mass of the tool after of each blow, can characterize a size of peening. To determination of sufficiency of hardening was used a criterion of increase a hardness of a site of a processed wall on which she has thinning from corrosion. This criterion is formulated from a condition of achievement of equal hardness of a processed site of a wall and the faultless wall having nominal thickness. The criterion is based on a special case of a boiler formula for a pipe of infinite length. According to it in criterion the generalized equivalent of hardness applied to the median diameter of a pipe to what the concentrated stretching effort is made. Here is possible to use, for example, the average hardness size on thickness of a wall as it is known that it is correlated, for example, with a fluidity limit [37]. But in criterion use a hardness of a surface on which is make peening. It do only on the ground that residual

tension created at a peening in a wall of a pipe has the same sign, as tension from loading by its internal pressure, that is, Baushinger's effect is always excluded. However even if such condition is admissible, increase in superficial hardness isn't proportional to the increase of average hardness on thickness of wall. It is known that hardening at superficial plastic deformation asymptoticly decreases into depth. Function of this decrease at the majority of metals and alloys is nonlinear transcendental function of distance from a surface some parameters of which should be defined experimentally. Therefore is necessary the knowledge of all parameters of function of hardening on thickness. It demands preliminary laboratory researches on blow of a sample of steel from which is made a pipe [38]. Otherwise control of hardening will be approximate and doubtful. Besides, stabilization of static pressing of the manual tool is a task demanding special decisions [39]. That doesn't allow to use any known tool.In the researches described in work about of technology [6] is not offered a concrete method of carrying out laboratory researches applicable in the industry on peening and method of measurement of a temporary trend of frequency of blows which it would be possible to present at metrological examination.

2.2 Concerning the Tool

For the first time the kinematics scheme of the tool with a free impactive element (ball) was described in [17]. She describes oscillatory moving of a ball between a processed surface and a surface of a source of fluctuations. To such tool is necessary the fixed position concerning a processing surface with existence of strictly certain gap between a ball and the surface concerning which he makes oscillatory moving. Providing of the fixed situation will be complicated at using this device as the manual tool for processing of surfaces with an irregular profile. In case of absence of the fixed situation there can be simultaneous mechanical contacts between a processed surface, a ball and a working end of a source of fluctuations regardless of a phase of oscillatory moving of the last. Power sources for each impact in the course of repeating blows (multiblows process) will be in that case:– movement of the center of mass of the tool in the blow direction if there is a component of a vector of gravitation in this direction;– symmetric, elastic fluctuations of a source concerning knots of the standing acoustic wave in it from the electro-acoustic converter;– the external force of tool pressing – effort with which the operator presses the tool to object of processing, making work against forces of inertia of the tool at its rebounds after each blow to a surface.In the course of work the energy of impacts is allocated in processed object where it performs work of plastic deformation, and on the tool in the form of kinetic energy of the next rebounds. At a rigid design of the described tool the amortization of rebounds can be carried out only by the operator holding the tool and representing in relation to it the external force. Impact of vibrations will be more if the amplitude of the vibrating force transferred through the tool there will be more.

In the multiimpactive tool [2], impacting elements in the form of hinges are inserted into a special holder and have in it freedom of axial moving. In the course of work the tool nestles on a processed surface so that external end of any of hinges enters into mechanical contact with a processed surface and the internal end with the acoustic transformer that transfers energy of a source of oscillation into processed object at the expense of its rigidity. At such transmission of energy after each contact with the object also there is a tool rebound, at the expense of a part of energy of impact which wasn't spent for plastic deformation and object moving, and makes a part of kinetic energy at the beginning of impact which is proportional to a square of the Newtonian coefficient of restoration. Absence in a design of the tool of shock-absorbers and dampfers predetermines his excessive rigidity and weak protection of the operator from vibrations. It is necessary to notice that in a case when the tool moves to operating time concerning of processed object excluding participation of the operator by means of any means, vibrating influence will feel the last and that can lead to its damage or destruction if is not accepted special measures of protection from vibrations.

In the tool described in [1], free volume between an internal wall of the casing and a source is intended for circulation of liquid of the cooling at the expense of which the heat from the electro-acoustic converter are deducing from the casing. In this tool for decrease of vibrations is low- and high frequency, arising at work and influencing the operator, the source of oscillations is connected with the tool casing through the elastic ring compacting located between it and the casing of the tool and near with knot of oscillatory displacement of the transformer of oscillatory speed. Besides, in the tool is placed filled with air the elastic camera in which is rested one end the converter. Thus the source of oscillation has possibility of axial moving at which elastic ring plays a role of compacting of the system of liquid cooling of tool, elastic camera - shock-absorber role. The length of this moving is set by the sizes of the camera. Decrease of level of vibrating influence on the casing of tool here is reached generally at the expenses of a dispersion of kinetic energy on a viscous and elastic friction of elements of design. But it reduces mechanical efficiency of the tool.

It is known that efficiency of multiimpactive processes depends on conservation of maximal energy in system or at the minimum of its dispersion [36]. In case of systems with ultrasonic oscillation the high dispersion coefficient of the tool in general can lead to degeneration of system with free hinges into system with way of introduction of ultrasound through constant mechanical contact which is less effective [16]. Besides, the large mechanic quality-factor serves by effective

means of decrease the influence of the vibration [40]. The scheme with such elements is used in the tools described in [41]. Their design is shown on fig. 1, and photo [42] on fig. 2.
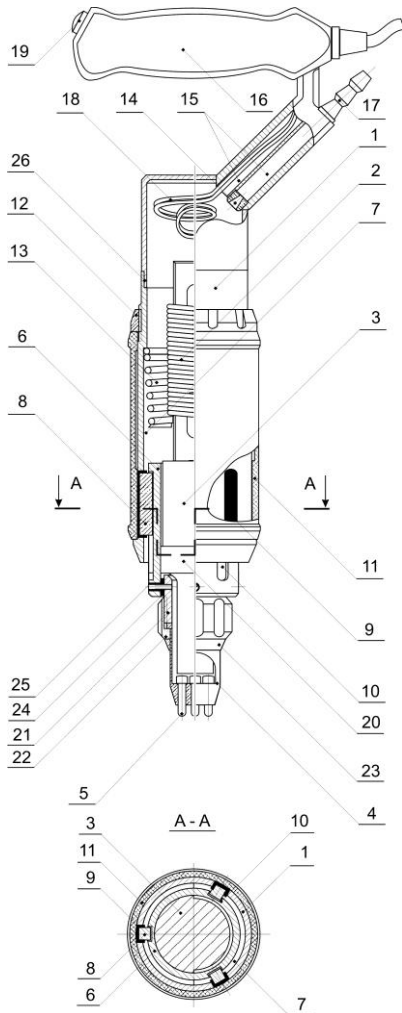

Figure 1. General view of the ultrasonic impactive tool.

Figure 2. A photo of the computerized complex for receiving an ultrasonic peening from [42].

The ultrasonic tool (fig. 1) contains the casing 1, the source of oscillations consisting of magnetostriction converter with a winding 2 and the acoustic transformer 3, placed in the casing and having concerning it possibility of axial moving, holder 4 with impact hinges 5. The source of oscillations is fixed in the plug 6, is placed in the casing with a gap 7 on directing slidings 8, which is made in the form of prismatic keys are put into grooves of the casing 9 through elastic linings and into deaf grooves 10 in the plug. The length of a groove in the plug is more than may move of the fluctuations source inside casing. Prismatic keys and elastic linings are kept in grooves of the casing by the second slight casing 11 which is fixed by means of a screw nut 12. The free moving of the plug is in addition limited by the spring shock-absorber 13. The cooling air moves through a throttle 14 which is fixed in one of two channels 15 in the basis of the handle of the tool 16. In the second end of this channel is established the union 17 for flexible hose with the compressed air. These elements of a design together with a gap between the plug and the casing represent a system of air cooling of a source of oscillations. Via the second channel in the basis of the handle 16 are deduced a wires 18 winding of the source of oscillations. In the handle 16 the switching device 19 with a trigger of the system of remote start of the ultrasonic generator is located. The source of fluctuations is fixed in the plug with a tightness in a flange 20 on acoustic transformer 3 in a place of antinode of cross-section fluctuations.

The holder 4 with impact hinges 5 is inserted in the nut 22 by means of the lock ring 23, and has possibility to turn round at the weakened nut to be turned on the necessary corner concerning the tool handle. Transitional the branch pipe 21 is fixed in the plug 6 through an elastic cuff by 24 hairpins 25. For convenience of assembly of the tool the casing is consists

of two parts connected among themselves by demountable connection 26. After that cooling air arrives in the tool via the branch pipe 17 and leaves it through a gap between the casing and the plug, the mobile part of the tool consisting of a source of oscillation, the plug and transitional branch pipe, a holder with a nut, a lock ring and holder of blow hinges, move under the influence of pressure of the air in casing of the tool forward. The rotary moving of the plug in the casing which can become the cause of wires breakage of a source of oscillation 18 is precluded by the keyway connection consisting of the keys 8, grooves in the casing and in the plug. The length of a longitudinal course of a mobile part of the tool is limited to size on which the length of grooves in the plug exceeds length of the directing. Thus, loss of a mobile part of the tool is excluded from the case under the influence of superfluous pressure of air in the tool. After generator start the source starts to make oscillating motions concerning knots of longitudinal fluctuations, on one of which the plug is fixed. Thus if contact of a forward end of the transformer to hinges is absent, is absent also a vibration of the casing of the tool in the longitudinal direction as fluctuations of a source are mutually counterbalanced concerning the center of its mass. From the cross-section vibrations caused by cross-section fluctuations of a source and flexural fluctuations of the plug, the casing is protected by elastic linings 9. When to the casing of the tool is attached the external force, a source, impact hinges and the object of processing is enter in the mechanical contact having effort equal to external force. Under these conditions as it was described above is begins the process of blows being accompanied by rebounds of initial position of the source. If thus external force exceeds pressure force of air on a mobile part of the tool then the free movement of plug is chosen and the internal end of the plug enters into mechanical contact with the shock-absorber 13. From the moment of the middle of each blow, under the influence of the energy reserved in system during blow at the expense of elasticity being in mechanical contact: the object of processing, a hinges and a source of oscillations occurs recurrent moving of a mobile part of the tool from object – a rebound. The moving part has piston impact on air in the casing, and in a casing when the free moving is chosen – pressure upon the shock-absorber, carrying out thus the work against elastic forces, that is, transformation of kinetic energy of the moving weight into potential energy of the its spatial situation. The parts of volume of the air being in the tool are forced out through a gap between the casing and the plug. This process occurs practically without energy dispersion as viscosity of air is small. After pressure force of air (or pressure of air and the shock-absorber) will counterbalance force of inertia of a moving part of the tool, air in the casing will start to restore the initial volume, giving to the plug and everything that on it is fixed, acceleration of an opposite sign. As at work flexural fluctuations are forming in the plug concerning a place of its fixing, therefore a dispersion of energy on a plug friction about the directing practically is absent. Because of plug vibration the operating on a motionless part of the tool (the casing) the vibrating force which is equal to a difference of average values of forces of reaction of return and forward movements, thus will be almost absent.

Such tool can work in three modes:–an optimum mode without shock-absorber participation;–the mode in which the free moving is came to an end and participates elasticity of the spring shock-absorber;–the mode in which all course is came to an end and absent amortization and damping of blows, and loadings are transferred to the casing through almost rigid communication. This mode is similar to operation of the tool with the rigid fastening, considered above. There are less "rigid" kinematic schemes of the ultrasonic impactive tool, for example, described in [43]. Their work corresponds to the second of the described modes of the tool represented on fig. 1.From the analysis of all these kinematics schemes clearly that decrease of vibroloadings on the casing of tool inevitably leads to losses of efficiency of work, especially, if between the casing and the oscillatory element which is coming into contact to hinges, there is a dissipative element of type a cataract. Kinematic schemes of the tools are shown on fig. 3.
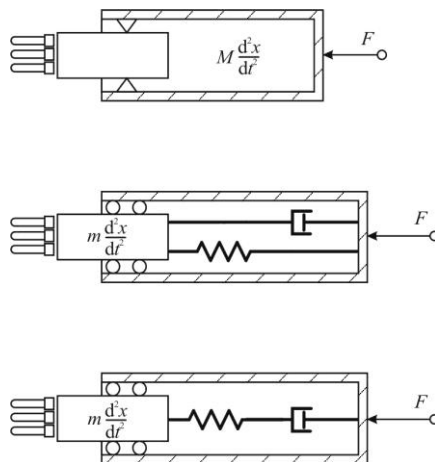

Figure 3. Kinematic schemes of ultrasonic impactive tools.

2.3 Concerning Ensuring of Corrosion Protection

Concerning measures of corrosion protection of welded seams after their processing by the ultrasonic tool from patent and scientific and technical literature it was possible to find out a little.

At repair work with use of electric welding and the subsequent impactive ultrasonic processing of seams [9,29] in an oil and gas complex use a peening [6]. For isolations of pipelines which protect them from direct contact with moisture are used different covers. A welded connection can have contact to moisture of air, the soil and is direct to water, including sea water which, being a solution of electrolytes can cause the increased corrosion in places of welding.

The task becomes complicated at constructional steels where at creation of peening by the impactive tool transferring the blows by means of hinges, on a surface is formed the thin scaly layer with the changed structure of metal [6] (Fig. 4).

It formed as a result of flattening of the metal which is squeezed out to a perimeter of a hole of deformation and pressed down by the subsequent blows of tool which is moving concerning a surface. Having scaly structure with flakes which almost parallel the surface, this layer has the developed surface and possesses the increased sorption ability. At absence of measures of corrosion protection this layer can quickly corrode itself and promote corrosion of the main metal.
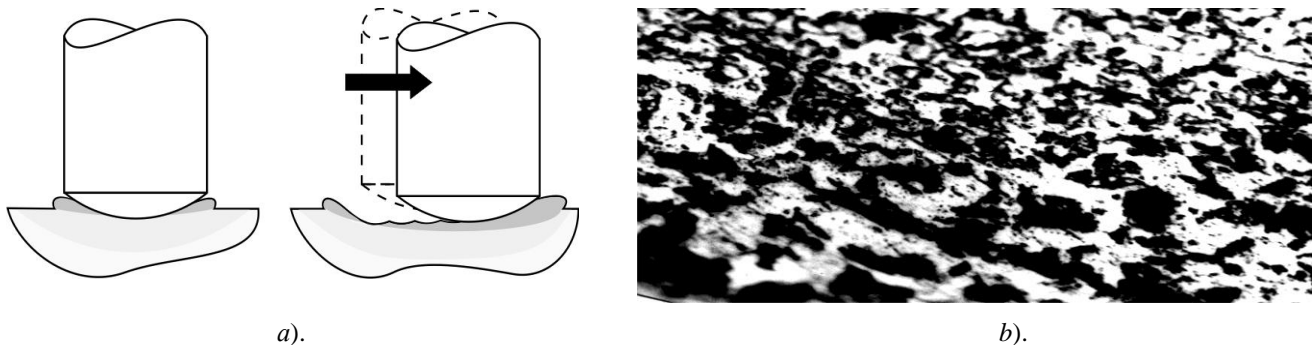

a).   *b*).

Figure 4. The scheme of formation of a scaly layer (*a*) and a metallographic speciment of the cross-section (*b*). In a scaly layer in the processed metal is created a peening with another structure of metal.

3. Teoretical Researches

3.1 Mathematical Model of Ultrasonic Impactive Processing

The model is intended for finding the constants characterizing an hardening by plastic deformation by the ultrasonic impactive tool of constructional steels. Three constants are by means of recursive adaptation of model to function of a temporary change of the frequency are received at the stand experimentally. Was used the theory of a hypercycle of multiimpacts by a flat stamp under the influence of a power source making symmetric flat and elastic fluctuations concerning the center of mass of the tool [6].

Function of relative hardening with empirical coefficient c_0 (the first constant of steel) is formalized as follows. For calculation of distribution of density of deformations in the blow direction conformal transformation of a strip with a cross-section cut of the complex plane $z(x, jy)$ on a strip of identical width of the another complex plane $\zeta(\xi, j\eta)$ is accepted:

$$\zeta = \frac{2}{\pi} \mathrm{Arth}(\sin^2 \frac{\pi u}{2} + \cos^2 \frac{\pi u}{2} \mathrm{th}^2 \frac{\pi z}{2})^{0,5},\tag{1}$$

where u – residual deformation under blow hinges (deposit).

Unlike used in [6] where it was borrowed from [44], this function has the analytical decision, as processing is conducted by a stamp with a spherical surface of contact, i.e. having the negligible cross-section size in comparison with thickness of processed object. The area ζ possess of a homothetic with factor 1 in any its point and relative hardening can be defined from calculation of the corresponding integral as a difference of values of function (1) in extreme points of straight line on which is carried out the integration, divided on length of that line on an imaginary axis:

$$s \qquad s = c_0^{-1} \, \mathrm{Im} \int_u^{c_0+u} \frac{\mathrm{d}\zeta}{\mathrm{d}z}\,\mathrm{d}z = \frac{\zeta|_u - \zeta|^{c_0+u}}{jc_0}\tag{2}$$

After inserts ζ from expression (1) and trigonometrical transformations the function (2) takes a form:

$$s = \frac{2}{\pi c_0}\mathrm{arctg}[(\frac{\sin \frac{\pi c_0}{2} + \cos \frac{\pi c_0}{2} \sin \frac{\pi u}{2}}{\cos \frac{\pi u}{2} - \mathrm{tg}\frac{\pi c_0}{2}\sin \frac{\pi u}{2}})^2 - \sin^2 \frac{\pi u}{2}]^{0,5}\tag{3}$$

Effective value of oscillatory speed of elastic fluctuations during contact of blow hinge, a power source and processed object is calculated from intensity of vibration and speed of distribution of elastic fluctuations in processed steel. As it is impossible to measure directly parameters of fluctuations with which energy is transferred by a source into steel during contact and what its part is spent on hardening, to the speed of a rebound is entered the factor of proportionality c_1, being the second by an empirical constant of steel. The expression for it has a form:

$$V = \frac{c_1}{R}(\frac{P}{\pi})^{0,5}[\frac{(1+v)(1-2v)}{\rho Es(1-v)}]^{\frac{1}{4}},$$ (4)

where: ρ – density of steel, kg/m^3; E – module of longitudinal elasticity, Pa; v – Poisson's factor, unit; P –mechanical capacity of the tool, W; R – radius of the end of blow hinge, m. A susceptibility of the steel to compression under blow (compressibility) is calculated from [6]:

$$\beta = \frac{1-v}{Es}$$ (5)

Then increments of residual deformation and the time of hypercycle for individual cycle are equal:

$$\Delta\varepsilon = c_2 V(\beta\frac{m}{R})^{0,5}$$ (6)

$$\Delta\tau = \frac{mV}{mg+F} + \pi(\beta\frac{m}{R})^{0,5}$$

where: F – force of pressing of the tool, is enclosed to cent of its masses; g – gravitational constant; m – mass of a mobile part of the tool; c_2 – the coefficient of proportionality being the third constant of steel.

Of (2) – (6) hypercycle of loading of a sample repeatedly n times striking into it of blow hinge will consist of $i+1^{-th}$ of elementary cycles, and in every $i+1^{-th}$ cycle the speed of a rebound, a deposit and its duration are set recursively:

$$V_{i+1} = s_i R^{-1}\pi^{-0,5}P^{0,5}\rho^{-0,25}(K+1,33G)^{-0,25}$$

$$u_{i+1} = u_i + \Delta\varepsilon_i$$ (7)

$$\tau_{i+1} = \tau_i + \Delta\tau_i$$

where K, G – the module of elasticity volume and the shift module, Pa, respectively.
Change of frequency throughout a hypercycle for simplification of procedure of adaptation of model to natural bench tests is

approximated by exponential dependence of linear function of time $t_i = \tau_n\frac{i}{n}$

$$f = e^{\alpha_0+\alpha_1 t},$$ (8)

where coefficients α_0 and α_1 are defined from expressions:

$$\alpha_0 = \frac{\sum_i t_i^2 \sum_i \ln f_i - \sum_i t_i \sum_i t_i \ln f_i}{n\sum_i t_i^2 - (\sum_i t_i)^2}$$ (9)

$$\alpha_1 = \frac{n\sum_i t_i^2 \ln f_i - \sum_i t_i \sum_i \ln f_i}{n\sum_i t_i^2 - (\sum_i t_i)^2}$$

The dot set of the reference points limiting individual cycles of blows form from empirical data representing a vector-columns a of sizes of noise signal, written down with a certain frequency during of a work of one blow hinge with a flat end in the form of a flat circle on a sample of steel, as:

$$r_i = \begin{cases} \begin{cases} 1, \text{if } a_i a_{i+1} > 0 \\ 0, \text{if } a_i a_{i+1} \le 0 \end{cases} & \text{if } \int a\, dt > 0 \\ 0, \text{if } \int a\, dt < 0 \end{cases}$$ (10)

where $i = 1\ldots f_m T$ – quantity of made with frequency f_m of noise measurements during a hypercycle T. Then is under

construction the function $I_{i+1} = I_i + \sum_i^{f_m T} r_i$ each value of which is constant on certain interval of time is equal to the sum of the

individual blows which have occurred during the time, corresponding to end of this a interval of time, being approximation of function of quantity of blows. From it by a summation is turns out set the empirical function of frequency of individual blows on a dot set of – a trend of frequency f^*:

$$f_j^* = f_m(\sum_i^{f_m T}\begin{cases} 1 \text{ if } I_i = j \\ 0 \text{ if } I_i \ne j \end{cases})^{-1}$$ (11)

where $j = 1...\sum_{i}^{f_m T} r_i$ – the number of individual blow. Time is defined, how the $\tau_j = j(\sum_{i}^{f_m T} r_i)^{-1} T$. These functions

graphically look as, for example, as is shown in fig. 5. Coefficients of function of approximating f^* find similarly how (9).

　　　　Adaptation of model consists in any recursive choice of constants of steel, which are satisfying to the solution of an optimizing problem of finding of a minimum of a difference between a theoretical and empirical trend of frequency of individual blows. Strategy of comparison and the corresponding criteria in a consequence should be chosen. At the solution of this task it will be possible to use known statistical criteria or to create original on their basis. At the chosen view of the analytical functions which approximate dot sets it is visually possible to consider as good coincidence the case which is simulated on an example is considered above (fig. 6).
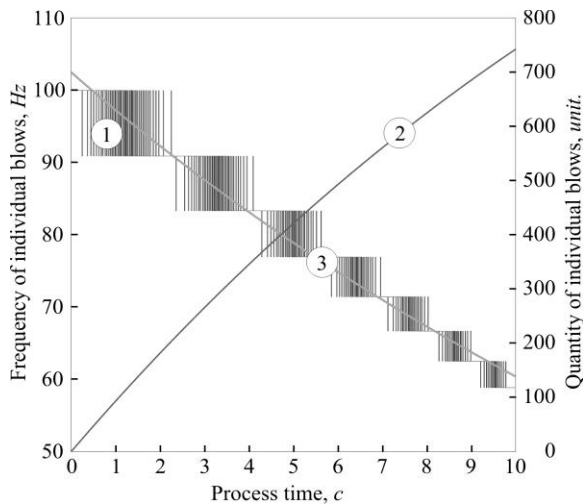

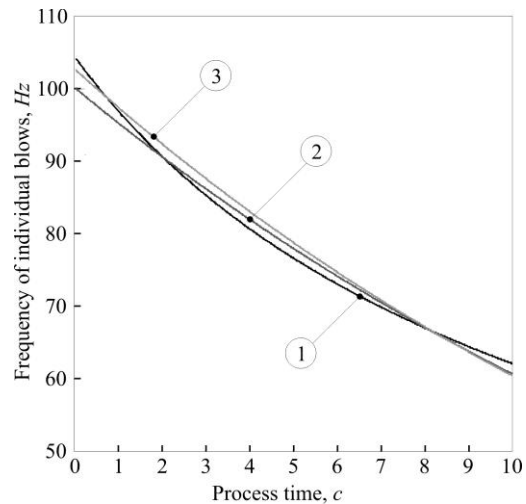| Figure 5. A graphic type of functions f^* (1), I (2) and the function approximating of f^* (3).	Figure 6. The functions of a theoretical trend of frequency (1), its approximations by a square polynom (2), of empirical trend of frequency (3).

　　　　This model of hardening in respect of the organization of control of process allows developing instructions on work on any objects with any ultrasonic impactive tool. For this purpose it is necessary to carry out laboratory researches on a hardening of a sample of steel or a welded seam and to construct computer model of the tool by which carry out processing. Development of the test model and package of the user programs of modeling and adaptation is a subject of separate work. Here closer attention was given to a control method without use of preliminary laboratory researches of steels. It can be realized by periodic check of performance of the special condition expressed by criterion that make on results of measurements of thickness of a wall alternating with measurements of hardness of its surface. Technically it gives the chance to make hardening of objects under control and without difficult in use and expensive equipments which demand of special conditions of use and qualified personnel, and also without special requirements to the ultrasonic impactive tool. Its essence consists in the following.

　　　　It is known that at polycrystalline materials of type constructional steels the easing of residual tension into depth from a surface in the field of plastic deformations is almost identical, and this tension according to the deformation theory is proportional to the sediment [45]. Therefore, at creation of mathematical model of deformation [46] distribution of tension in constructional сталях can be described within the theory of flat potential and to establish a type of analytical function of change of hardening along the normal to a surfaces. Such function are found by way of carrying out a computing experiments and natural measurements of gradients of hardness on inclined microsections of constructional steels. For practical use for hardening objects of thickness less 50 mm this function was approximated by exponential curve looking like a polynom of the third order from the measured thickness. As a result for a wide range of steels was formalized dependence of hardening from hardness of a surface and thickness of object which limits for a necessary and sufficient minimum the average extent of hardening on thickness. The hardness entering into it as parameter can be measured by any portable measuring instrument, for example, ultrasonic measuring instrument of hardness. The thickness – by portable ultrasonic measuring instrument whom it is possible to apply here as it is known that speed of the ultrasound in a zone of residual tension from plastic deformation in steels changes slightly. Using this dependence, it is possible to consider hardening sufficient when the preset value of relative hardening becomes less, than value of criterion [47]:

$$\mathbf{Cr} = \frac{h}{h_0} e^{3,2\delta - 7,2\frac{\delta^2}{\delta_0} + 4,0\frac{\delta^3}{\delta_0^2}}, \qquad (13)$$

where: h, h_0 – the current and initial values of hardness of a surface of a strengthened wall in a processing place, respectively (expressed in any units of hardness); δ, δ_0 – the current and initial values of thickness of a wall in a processing place, respectively (expressed in millimeters).For comparison of this method of control with [6] of sheet steel in accordance with GOST 5521-93 with initial hardness of h0 = 13,0±1,0 units of Brinnel's which was measured in five points of a surface, was made a samples. A third from them strengthened on the one hand approximately on 15%, supervising the hardening according to [6], a third – according to the described above and a third don't processing and used as control. As impactive tool was used the ultrasonic technological complex "Шмель МГ". On measurement of hardness of a surface in all cases was used the ultrasonic hardness measuring instrument. Average of a deposit at the hardening, calculated on five measurements of thickness and everywhere remained in admissibility of deviations of thickness in accordance with GOST 1497-84. By the universal test machine at samples was defined conditional limits of fluidity at stretching.

Table 1. Average results of hardening and tests of samples.

PARAMETER	Unit of measure	VALUE		
		Analogs of method	Developed method	Control
Residual deformation (deposit), $\delta - \delta_0$	*mm*	0,06±0,03	0,07±0,04	–
Hardness of a surface after hardening, h	*HRC*	18,0±2,5	21,5±2,5	13,0±1,0
Conditional limit of fluidity at stretching, $\sigma_{0,2}$	*N/mm^2*	271±7	301±8	235

From the table 1 is visible that the samples strengthened at compliance [6] maintain the mechanical tension which is not leading to emergence of appreciable residual deformations, big, than at control samples, but smaller, than at the samples strengthened with application of the new control method. And with this application a relative hardening of a surface of samples more. Comparative tests of hardening of zone near welded connections on plates from sheet steel in accordance with GOST 5521-93 were also made. A half of them processed the impactive tool of the ultrasonic technological complex "Шмель МГ", supervising the hardening by criterion (13) and superficial hardness. A half of samples with seams remained without processing and used as a control. Samples was loaded to a rupturing by the test machine (Fig. 7).

Table 2. Results of hardening and tests of samples to a rupturing.

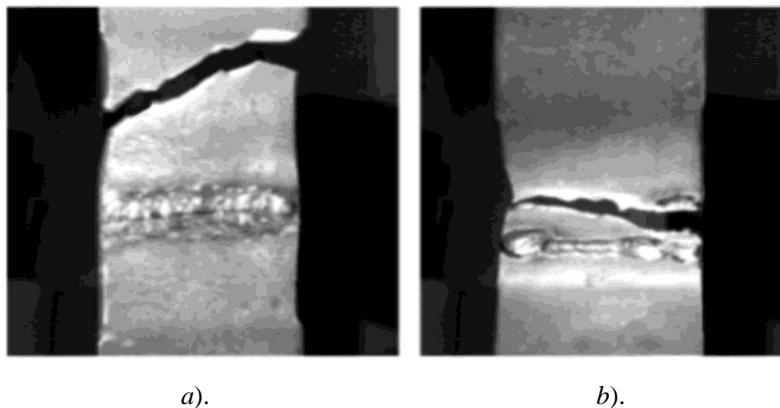| PARAMETER	Unit of measure	VALUE	
		Hardening	Control
Tension of the beginning of a rupturing	*N/mm^2*	558±11	479±5
Hardness of a surface after hardening	*HB*	170±5	133±4

a).   *b*).

Figure 7. Photos of a rupture of samples: *a*). a sample with the processed by impactive superficial plastic deformation of surface near a welded seam – destruction occurred on the unprocessed metal;
b). the sample without zone processing – a destruction occurred directly on that zone.

3.2 Example of Use of Offered Technology

For example, as at case is shown in [6], is required to restore struck with corrosion into depth of 2 *mm* the wall of a pipe of the main gas pipeline made of steel 17Г1С which have nominal thickness of 14 *mm*. For this purpose at first, for example, by portable device ТЭМП-4 measure hardness of a surface of a wall not on the struck area of h_0. For example, it is equal 195 *HB*. In a place of corrosion defeat the wall has thickness $\delta_0 = 14 - 2 = 12$ *mm*. According to a special case of a boiler formula for a pipe of infinite length to resist also as faultless wall to the stretching tension attached to the median line of diameter of a pipe, metal of the struck site should in 14 : 12 = 1,167 times be stronger. It is relative hardening which is demanded. The processing is make, for example, the same complex "Шмель МГ", consistently processing a surface of the struck site of the impactive tool, and alternate it with measurements of a hardness and of a thickness of a wall in a processing zone. For measurement of the last it is possible to use, for example, a portable ultrasonic device ТУ3-1. To the increase of reliability of measurements after carrying out some number of measurements of each of parameters is calculate its average value. Both named devices, having microprocessor management, allow making this procedure simple and can calculate average values yourself. Results of measurements give possibility to calculate the current size of criterion (13). For this purpose may be used any programmed calculator. For example after of the executed processing at the made measurement and calculation of averages of h and δ their current values, for example, is equal 219 *HB* and 11,95 *mm*, respectively. Value of criterion thus 1,147e − 0,039 = 1,103 that less, than 1,167. Then the next time carry out a stage of processing by the ultrasonic impactive tool of a surface of wall and again make measurements and calculations. For example this time h = 231 *HB*, δ = 11,90 *mm*. Then 1,262e − 0,076 = 1,170 > 1,167. That is, under condition of uniformity of a peening on all surface of the processed site which can be checked visually, it is possible to consider hardening sufficient.

3.3 Devices for Ultrasonic Impactive Superficial Plastic Deformation

The kinematic scheme of the ultrasonic impactive tool of the device «Gefest-400» (Fig. 1) is shown on the fig. 3 (below). This device is intended for use as the manual portable tool, therefore existence a cataract included consistently with an elastic element, in its kinematic scheme is quite justified. This scheme provides the best possible protection of the operator from influence of vibrations. However it doesn't provide the maximum efficiency of the tool as dissipates and extinguishes a part of kinetic energy of rebounds. Therefore more favorable from the point of view of a useful expenditure of energy it a scheme shown on fig. 8 *a*. In this scheme the effort of a statical pressing is set and stabilized by means of the elastic element (spring) is between object of pressing and the tool casing. Then the oscillatory system of a power source can be fixed in the casing motionlessly, for example, in the location of knot of oscillatory displacements. The tool of technology complex «Шмель-МГ» (fig. 8 *b*) is arranged just so. This complex was specially created for ultrasonic strengthening processing of welded connections at recovery operations of the main pipelines.

Table 3. Technical characteristics of the «Шмель-МГ»

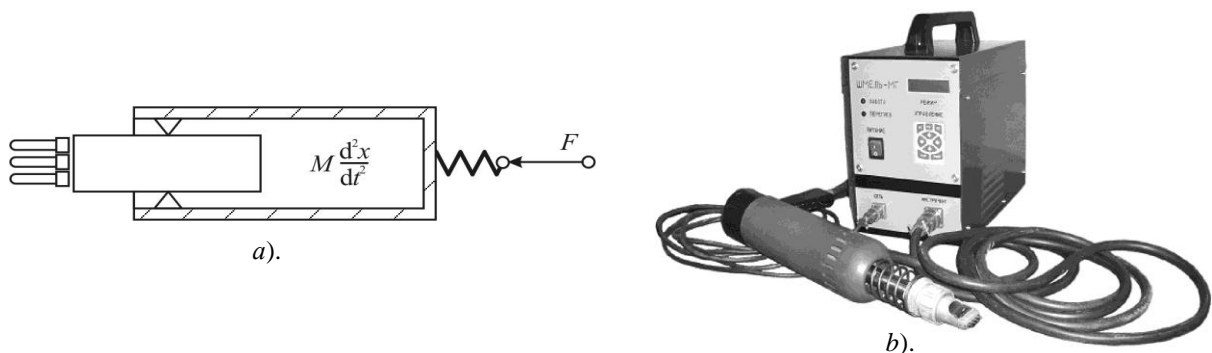| PARAMETER	Units	VALUE
Voltage of the generator	*V*	250
Frequency of supply voltage	*Hz*	50±1%
Frequency of the generator	*Hz*	22000
Power consumption	*W*	800
Overall dimensions:	*mm*	
– generator		350×270×180
– tool		455×80
Weight (general)		15,5

Figure 8. The kinematic scheme with the smallest expenditure of energy (*a*)
and a «Шмель-МГ» complex photo (*b*) with ultrasonic impactive tool corresponding to it.

3.4 Technology of Corrosion Protection of a Zone of Processing

In [6] the following hypothesis was put forward: « Being formed at surface of a metal as a result of superficial plastic deformation by the ultrasonic tool a superficial scaly layer, if his sate hydrophobic composition or a inhibitor of corrosion, can play a role of a peculiar sheeting». Therefore before beginning the processing of a surface of a wall by plastic deformation or in the course of it, it is necessary to put a thin layer of this or that composition on a processing surface. In the course of processing it will enter inside a scaly layer and is forming together with it an anticorrosive covering. It will give the chance to increase corrosion resistance of metal of the processed sites of a surface near a welded seam. It is known that for ensuring effective chemical protection of metal it is best of all to use anodic inhibitors of corrosion and to support concentration of inhibitor as is possible above therefore it is better to use a concentrate. For check of this hypothesis the accelerated corrosion tests according to GOST of 9.905-82 strengthened samples of trumpet steel 17Г1С in accordance with GOST 19281–89 were carried out. Were compared a specific losses of weight of metal from corrosion on a surface of the flat samples which are completely immersed at 72 o'clock in water solution 5% of sulfuric acid, 8% of hydrochloric acid, 3% of sulphate of iron and 2% of sodium of chloride to common weight. On prototypes by ultrasonic impactive tool serially is created a peening with increase in hardness at 20%. How a control was used the samples of steel without processing. On the samples which are simulating hardening without corrosion protection, a processing was made on a dry surface. On a part of the samples strengthened with taking measures of corrosion protection for creation of anticorrosive water-repellent properties was put a layer of lubricant ЦИАТИМ-221 (GOST 9833-80) on other part – saturated water solution of trisodium phosphate (GOST 201-76) which is anodic inhibitor of corrosion.

Table 4. Results of the accelerated corrosion tests

No	SAMPLE	The specific losses of weight, $mg/(dm^2 \cdot h)$
1.	Without processing (control)	$4,34\pm0,09$
With the peening which has been executed on:		
2.	dry surface	$4,59\pm0,17$
3.	to water-repellent film	$4,18\pm0,21$
4.	to film of anodic inhibitor	$3,51\pm0,12$

4. Conclusion

The technology of hardening by ultrasonic superficial plastic deformation for elimination of a tension of welded connections of different types on products from constructional steels and corrosion protection of these connections can effectively be used. By the most suitable device for the peening may be the ultrasonic apparatus «Шмель-МГ». The mathematical model of plastic deformation is adapted for process of processing of welded connections for removal of mechanical tension and corrosion protection at presence of the special stand allows in each case to create technology for work and control of sufficiency of hardening with high precision and reliability, and also without preliminary laboratory researches to formulate criterion of sufficiency of hardening for the same objects which can be used in the course of work and be calculated by means of the ordinary pocket calculator. At operative control of process of hardening both in that and in other cases it is possible to use standard portable measuring instruments of physical parameters: thickness of a wall and hardness of a surface. To protection of processed surfaces against corrosion very effectively application of anodic inhibitors of corrosion which are entered into a surface directly in the course of processing.

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