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Increasing Corrosion-Fatigue Strength of Long Cylindrical Products as a Result of Preliminary Strengthening by Joint Stretching and Twisting.

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ABSTRACT

The technology of strengthening long cylindrical items has been studied. It deals with creating a close-to-surface area in the item of favorable compressing residual forces due to successive elastic-plastic deformation, firstly by stretching and then followed by fixation of the reached longitudinal deformation during stretching, and twisting. A mathematical model of elastic-plastic deformation by joint stretching and twisting of a homogeneous cylindrical item has been created. Instead of the existing methods of strengthening that include single twisting of a stretched item, new methods, dealing with bidirectional twisting of a stretched item, have been developed. The created new technological methods ensure optimum distribution of residual axial stresses across the section of the item with the minimum residual shear stresses. Such distribution of residual stresses contributes to increasing the fatigue strength of the product. The results of corrosion fatigue tests have proven efficiency of strengthening by joint stretching and alternated twisting technology.

Keywords: joint tension and twisting, residual stresses, mathematical model of elastic-plastic deformation, corrosion-fatigue tests, fatigue strength, fatigue life, technology of strengthening.

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INTRODUCTION

In the Russian Federation, oil wells work round-the-clock, the majority being equipped with rod oil pumping installations. One of the main elements of such installations is a column with pumping rods [2]. Pumping rods operate in the conditions of cycling loading in corrosive environment that is sometimes very aggressive. Therefore, characteristics of corrosion and fatigue strength are very important for items like rods [4]. For improving corrosion and fatigue strength, various methods of strengthening are used.

Without special measures taken, fatigue failure usually starts from the surface [10]. Therefore, in order to increase the bearing capacity of the rod, it is first necessary to increase its fatigue resistance in the close-to-surface area. One of the most effective mechanisms for strengthening the close-to-surface area is creating axial compressing residual stresses [14], [16], [22], [9]. The widely known methods of strengthening include the methods of plastic deformation of the surface: shot peening, burnishing with balls or rollers, surface hardening by High Frequency Currents (HVC), etc. [15], [19], [26], [23], [20]. These methods make it possible to create rather significant residual compressing stresses in the close-to-surface layer of an item. With regard to pumping rods, shot peening and hardening the surface with HVC are used most widely. However, the disadvantage of these methods is the local nature of strengthening both along the length of the item (non-uniform distribution of residual stresses) and across the cross-section (only the thin surface layer is strengthened). After long operation of the item in aggressive environment (in case of rods, it means several years), gradual erosion inevitably occurs in the surface area, and the effect of strengthening is eventually lost.

The authors of this article have studied a method of strengthening long cylindrical rods, which is different from the above methods. The method consists in creating axial compressing residual stress in the close-to-surface area of the item, due to consequent elastic-plastic deformation by stretching followed by twisting of the stretched item. In this case, the uniform distribution of residual stresses is obtained along the length of the rod (provided the initial properties were uniform), and at the phase of stretching, restriking occurs, i.e., the spatial geometry of the long item is restored. The method features high feasibility, and strengthening has volumetric nature. The depth of the strengthened layer may reach 1/3 of the radius from the surface, which exceeds the depth of corrosion spots penetration, and prevents further development of cracks in the surface; therefore, the effect of strengthening is preserved for long operation of the item. Currently, this method is used for restoring serviceability of used rods that have been used for less than their life cycle [1]. Modeling and optimization of the process of recovering workability of the used pumping rods are described in work [8].

However, existing methods of strengthening that include single twisting (in one direction) of a preliminarily stretched item, cannot be regarded efficient. Due to the non-uniformity of initial properties along the length of the rod, there is a risk of forming necks and even destruction of the body of the item in the process of strengthening. Therefore, the twisting angle is limited, which does not make it possible to create enough axial residual stress that could significantly increase corrosion and fatigue strength of the item. Besides, except for the fatigue tests of several recovered rods performed under the supervision of professor N. N. Wasserman [1], there is no other study that would prove actual efficiency of such strengthening technology. The possibilities of the technology themselves have been insufficiently studied theoretically, and have been very poorly proven experimentally.

Thus, the task of developing a new method that on the one hand would preserve the existing advantages of the technology of strengthening by joint twisting and stretching, and on the other hand would make it possible to significantly increase the corrosion and fatigue strength of the item and its cyclic durability, is relevant.

The central idea of the work is the use of alternated twisting in the process of strengthening by both twisting and stretching.

METHODS

The regularities of materials behavior after joint stretching and twisting were studied in many works, for example [17], [12], [18], [21], [24], [25]. Most of them present both experimental and modeling data, but the focus of these works is somewhat different. They mainly study the area of significant plastic deformation and the process of deforming by joint stretching. However, they do not consider twisting from the point of view of creating a favorable field of residual stress in the item, which would make it possible to increase fatigue strength, i.e., they are not focused on the strengthening.

The authors of this article in first performed theoretical and experimental study of the behavior of thin-walled tubular samples in the conditions of joint stretching and twisting. A mathematical model of elastic-plastic deformation by stretching and twisting was built for a thin-walled tubular item, based on the theory of plastic flow [7]. The areas of the model applicability are single-axis stretching, pure shear, and joint stretching and twisting.

The main provisions of the developed mathematical model are:

1. The stress-strain state (SSS) in case of joint tension and twisting in the cylindrical coordinate system (r, ϕ, z) can be characterized by the following components of stress and strain:

$$\sigma_r = \sigma_\varphi = 0,\ \ \sigma_z = \sigma,\ \ \tau_{rz} = \tau_{\varphi r} = 0,\ \ \tau_{z\varphi} = \tau,$$
$$\varepsilon_z = \varepsilon,\ \ \varepsilon_r = \varepsilon_\varphi = -\mu \cdot \varepsilon_z = -\mu \cdot \varepsilon,\ \ \gamma_{rz} = \gamma_{\varphi r} = 0,\ \ \gamma_{z\varphi} = \gamma,$$

where σ and τ are normal (axial) and tangential shearing stress in a point of the body, ε and γ are full frontal and full shear deformation at a point of the body, μ is the Poisson's ratio (for plastic strains component μ= 0.5).

2. The influence of time factor is insignificant, and the acceptable error can be neglected.

3. The beginning of plastic flow is not determined, the total strain along the way of loading consist of elastic and plastic components:

$$\varepsilon = \varepsilon_e + \varepsilon_p, \qquad d\varepsilon = d\varepsilon_e + d\varepsilon_p,$$
$$\gamma = \gamma_e + \gamma_p, \qquad d\gamma = d\gamma_e + d\gamma_p, \tag{1}$$

where dε and dγ are increments of longitudinal and shear deformations, index "e" marks elastic components of deformations and their increments, index "p" marks plastic components.

4. The hypothesis of existence of a single curve is considered fair. The SSS is considered as a state that is equivalent to single axis stretching. The analogs of voltages intensity (σ_{ek}) and increments of intensity of plastic deformation ($d\varepsilon_{ek.p}$) are taken as equivalent voltage (σ_i) and the increment of equivalent plastic deformation ($\overline{d\varepsilon_{ip}}$), which, for the case of joint stretching and twisting, are described by dependencies

$$\sigma_{ek}(\sigma,\tau) = \sqrt{\sigma^2 + (K_1 \cdot \tau)^2}\ , \qquad d\varepsilon_{ek.p} = \sqrt{d\varepsilon_p{}^2 + (K_2 \cdot d\gamma_p)^2}\ , \tag{2}$$

where K_1 and K_2 are dimensionless coefficients, according to the theory of flow: $K_1 = \sqrt{3}, K_2 = \frac{1}{\sqrt{3}}$ (experimentally confirmed for the material studied).

5. The material is considered uniform and initially isotropic.

6. The relations between voltages and deformations and their increments are defined by Hooke's law for stretching and for pure shear

$$\sigma = E \cdot (\varepsilon - \varepsilon_p), \qquad d\sigma = E \cdot (d\varepsilon - d\varepsilon_p),$$
$$\tau = G \cdot (\gamma - \gamma_p), \qquad d\tau = G \cdot (d\gamma - d\gamma_p), \tag{3}$$

where dσ and dτ are increments of normal and tangential shear stresses, E and G are Young's and shear moduli.

7. The diagram of plastic deformation is described by the differential equation:

$$\frac{d\varepsilon_{ek.p}}{d\sigma_{ek}} = f_1(\sigma_{ek}) \ \text{ at } \ d\sigma_{ek} \ge 0, \qquad \frac{d\varepsilon_{ek.p}}{d\sigma_{ek}} = 0 \ \text{ at } \ d\sigma_{ek} < 0, \tag{4}$$

where $f_1(\sigma_{ek})$ is the first defining function of the model that works in case of active loading, and is equal to zero in case of unloading; $d\sigma_{ek}$ is the increment of equivalent stress.

8. It is assumed that unloading obeys the linear elastic law.

9. The ratio of the increment of shear plastic deformation to the increment of longitudinal plastic deformation is a function of acting loads, i.e., it is described by a differential equation of the following form:

$$\frac{d\gamma_p}{d\varepsilon_p} = f_2(\sigma, \tau) \tag{5}$$

where $f_2(\sigma, \tau)$ is the second defining function of the model.

10. As a result, the increment of equivalent plastic deformation is expressed by the following relationship:

$$d\varepsilon_{ek.p} = d\varepsilon_p \cdot \sqrt{1 + \left(K_2 \cdot f_2(\sigma,\tau)\right)^2} = d\varepsilon_p \cdot f_3(\sigma,\tau), \quad \text{where} \quad f_3(\sigma,\tau) = \sqrt{1 + \left(K_2 \cdot f_2(\sigma,\tau)\right)^2} \tag{6}$$

11. The final expressions that relate the increments of longitudinal and shear plastic deformation with the values of stress:

$$d\varepsilon_p = \frac{\sigma \cdot d\varepsilon \cdot E \cdot f_1(\sigma_{ek}) + K_1^2 \cdot \tau \cdot d\gamma \cdot G \cdot f_1(\sigma_{ek})}{f_3(\sigma,\tau) \cdot \sigma_{ek}(\sigma,\tau) \cdot \text{sign}(\sigma) + \sigma \cdot E \cdot f_1(\sigma_{ek}) + K_1^2 \cdot \tau \cdot f_2(\sigma,\tau) \cdot G \cdot f_1(\sigma_{ek})} \tag{7}$$

and from (5): $d\gamma_p = d\varepsilon_p \cdot f_2(\sigma,\tau)$

For each specific material, the most suitable determining functions $f_1(\sigma_{ek})$ and $f_2(\sigma, \tau)$ are to be taken without changing the model itself. For the studded material, structural steel 15Cr2MnMoV without yield strength, the first function was taken as dependence:

$$f_1(\sigma_{ek}, A, m) = A \cdot \left(\frac{\sigma_{ek}}{\sigma_{0.2}}\right)^m \tag{8}$$

where $\sigma_{0.2}$ is the yield strength of the material, m is power exponent, A is the parameter expressed by $\sigma_{0.2}$ and m from the condition of the chart of plastic deformation passing through the point with coordinates (0.002; $\sigma_{0.2}$):

$$A = (m+1) \cdot \frac{0.002}{\sigma_{0.2}} \tag{9}$$

Replacing $f_1(\sigma_{ek})$ with $f_1(\sigma_{ek}, A, m)$ is used for describing the Bauschinger effect, i.e. parameters A and m that determine the slope of plastic deformation curve can vary depending on the stage of deformation.

The second defining function was taken as dependence:

$$f_2(\sigma,\tau) = B \cdot \left(\left|\frac{\tau}{\sigma}\right|\right)^q \cdot \text{sign}\left(\frac{\tau}{\sigma}\right), \tag{10}$$

where B and q are dimensionless parameters.

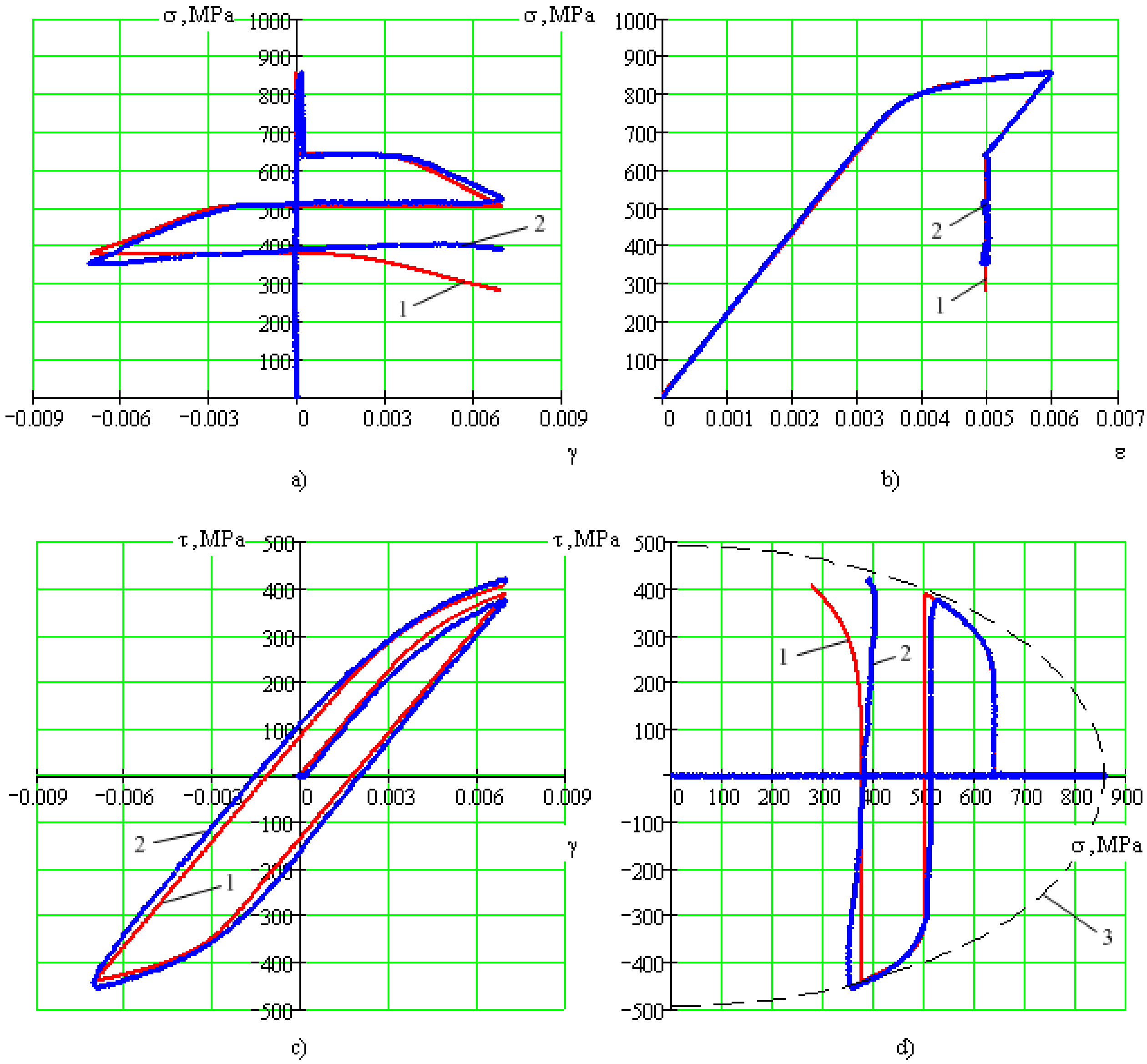

Figure 1. Dependency graphs: a) σ – γ, b) σ – ε, c) τ – γ, d) τ – σ in testing sample of 15Cr2MnMoV steel in the sequence: elongation up to ε = 0.006 (corresponds to $\sigma_{0.2}$), unloading up to ε = 0.005 (corresponds to σ = 0.75·$\sigma_{0.2}$), fixation of reached strain ε at the constant level, twisting up to γ = γ_a (γ_a= 0.007), twisting in the opposite direction γ = – γ_a,, twisting in the original direction to γ = γ_a. 1 - model, 2 - experiment, 3 - Mises ellipse: $\sigma^2 + 3\cdot\tau^2 = \sigma_{0.2}^2$ ($\sigma_{0.2}$ = 855 MPa).

The input parameters of the model are the values of full deformations achieve that at each stage of the deformation. The material parameters are mechanical characteristic of the material (E, G, $\sigma_{0.2}$) and coefficients of defining functions (8) and (10). The model outputs dependencies between voltage and deformations. For solving equations, the method of finite differences is used; the process of numerical computation is implemented in the form of a program made in the MathCAD SW package

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The necessary tests on thin-walled tubular samples for defining material parameters of the model and confirming adequacy of obtained solution were performed in the Center of Experimental Mechanics of the Perm National Research Polytechnic University, using the universal two-axis servo-hydraulic testing system Instron 8850. The tests were made with the use of a suspended extensometer that makes it possible to record the longitudinal and shear deformations directly in the working area of the sample. This excluded the measurement errors caused by the yield of the loading system and poor fixation of the sample in grips.

Both existing methods of deformation that are used in the technology of strengthening in question including stretching, fixation of the achieved longitudinal deformation on constant level followed by single twisting and developed new methods including stretching, fixation of the longitudinal deformation at the constant level followed by alternating twisting, have been studied.

The theoretical solution shows rather accurate correspondence to the results of experiments at the stage of stretching, partial loading after stretching (if such a stage is present), and consequent two stages of alternating twisting, where intensive decrease of normal stresses is observed (Figure 1). In the third stage of twisting, deviation of results is observed, where, according to the experiment, normal stress remains virtually the same, even the opposite: it increases first, which is possibly caused by anisotropy of the properties induced in the process of deformation. However, the model describes the $\tau - \gamma$ loop rather accurately in all stages. this is achieved due to the fact that in the third stage of twisting parameters *A* and *m* in the first defining function f1 (σ_{ek}, A, m) are decreased, while in this stage of stretching, and the first two stages of twisting they remain the same.

From the point of view of rods strengthening itself, it is the decrease of the normal stress that is of interest, since in this case, due to decrease of the longitudinal elastic deformation, the plastic deformation gets accumulated, which in the long run is related to forming residual axial stresses. Thus, only the stages of stretching and consequent two stages of twisting may be regarded as useful i.e., those within the limits of which the model describes the results of the experiment rather accurately. The third stage of twisting is further made only partially, within the limits when the correspondence of the model in the experiment may be regarded satisfactory.

In the other variants of initial stretching stress and the amplitude of twisting, the theoretical solution also confirms its adequacy showing rather high correspondence to the results of experiments at the stages of defamation that are of interest for strengthening items (stretching followed by two full twisting stages and the third partial twisting stage).

RESULTS AND DISCUSSION

Research Of The Process Of Strengthening Uniform Rods With Round Cross Section By Joint Stretching And Twisting

In the second stage, the process of strengthening uniform rods with round cross section by joint stretching and twisting was studied. To do so, a mathematical model of deforming a round cross section rod was built, based on the model of deforming a thin-wall tubular item.

<u>The main provisions of the developed mathematical model are:</u>

1. A solid round cross-section rod is divided into n thin-walled cylinders with average radius R_i and wall sickness δ_i where $\delta_i << R_i$. For every cylinder, they are defined according to formulas:

$$R_i = \frac{Rv_i + Rv_{i+1}}{2}, \qquad \delta_i = Rv_i - Rv_{i+1}, \tag{11}$$

where Rv_i is the i^{th} cylinder's outer radius determined by the formula:

$$Rv_i = RN \cdot \prod_{j=1}^{i} \left(1 - \frac{1}{n} \cdot (j-1) \right), \tag{12}$$

where RN is the largest outer radius, i.e. the radius of the rod itself.

The model of deformation of a thin-walled tubular item discussed earlier describes deformation of each thin-walled cylinder separately.

2. The hypothesis of flat sections and straight radii is considered fair. As a result, all thin-walled cylinders receive the same common longitudinal deformations, and the shear deformations relate between themselves in a linear relationship.

$$\varepsilon_i = const, \qquad \gamma_i = \frac{R_i}{R_{\max}} \cdot \gamma_{\max}, \tag{13}$$

where γ_{max} is the shear deformation of the outer cylinder, R_{max} is the average radius of the outer cylinder.

3. The magnitude of the longitudinal force (N) and torque (M) in the process of loading are determined by the ratios:

$$\mathrm{N} = \sum_i \left(2 \cdot \pi \cdot R_i \cdot \delta_i \cdot \sigma_i\right), \qquad \mathrm{M} = \sum_i \left(2 \cdot \pi \cdot (R_i)^2 \cdot \delta_i \cdot \tau_i\right) \tag{14}$$

4. When external tensile force and torsion moment are removed, elastic unloading occurs, after which residual deformation and residual stresses remain in the item (in case of a non-elastic deformation at the stage of loading). In accordance with the theorem of unloading [7], the values of residual deformations (ε_{os}, γ_{os}) are defined as the differences between the values of deformations under load and the values of removed deformations during unloading. They are finally reduced to the following expressions:

$$\varepsilon_{os} = \frac{\sum_i \left(R_i \cdot \delta_i \cdot \varepsilon_{pi}\right)}{\sum_i \left(R_i \cdot \delta_i\right)}, \qquad \gamma_{os} = \frac{\sum_i \left(R_i \cdot \delta_i \cdot \gamma_{pi}\right)}{\sum_i \left(\frac{R_i^2}{R_{\max}} \cdot \delta_i\right)} \tag{15}$$

In this case: ε_{os} is the residual longitudinal deformation in all cylinders, γ_{os} is the residual shear deformation in the outer cylinder.

5. From the values of residual deformations found, and the values of plastic deformation in each ith cylinder, the values of residual stresses are calculated:

$$\sigma_{osi} = E \cdot \left(\varepsilon_{os} - \varepsilon_{pi}\right), \qquad \tau_{osi} = G \cdot \left(\gamma_{os} \cdot \frac{R_i}{R_{\max}} - \gamma_{pi}\right), \tag{16}$$

where σ_{osi} and τ_{osi} are residual axial and residual shear stresses in the i-th cylinder.

The input parameters of the model are: the level of stretching stress from at which twisting starts, and the values of shear deformation achieved at each stage of twisting. The result is the distribution of residual stresses along the radius of the item, and dependencies of the longitudinal force and the torque on the twisting angle ϕ, where $\varphi = \frac{\gamma_{\max} \cdot l}{RN}$, and *l* is the length of the working part of the item. The step-by-step process of calculating all the parameters is implemented in a program made with the MathCAD package.

The results of testing samples with round cross-section, performed, as before, at the Center of Experimental Mechanics of the Perm National Research Polytechnic University in testing system Instron 8850, confirmed adequacy of the mathematical model and the area of deformation methods, where it describes the behavior of material with the accuracy acceptable for practice. Figures 3 and 4 show comparison of the theoretical and experimental dependencies diagrams.

The rational methods of strengthening are such methods that ensure the most favorable distribution of residual stresses along the radius of the item.

The criteria of favorable distribution of residual stresses are:

- In the close-to-surface area, residual axial compressing stresses with the maximum absolute value are induced, which increase corrosion fatigue strength of the item.
- In the core of the rod, the minimum residual axial stretching stresses are induced, which have negative effect when working stresses in the item (axial tensile stresses arising in the pumping rod) are interposed on them;
- The core of the road remains elastic (has elastic core)

- In the close-to-surface area, residual tangential stresses with minimum absolute value are induced, which negatively influence the characteristics of the fatigue strength;
- This leads to a comparatively deep occurrence of residual axial compressive stresses, which do not allow new corrosion cracks develop in the close-to-surface area.

Basing of these criteria for each of the tested strengthening methods (by joint stretching and single twisting, joint stretching and alternate twisting, stretching and alternated twisting with equal amplitude) the rational methods of deformation are defined for a homogeneous rod. Figure 2 shows the dependence of the residual axial compressive stress on the surface of the item value on the amplitude of shear deformation in case of strengthening by joints stretching and alternate twisting (the range of rational methods is: γ_a = 0.007 ÷ 0.009).

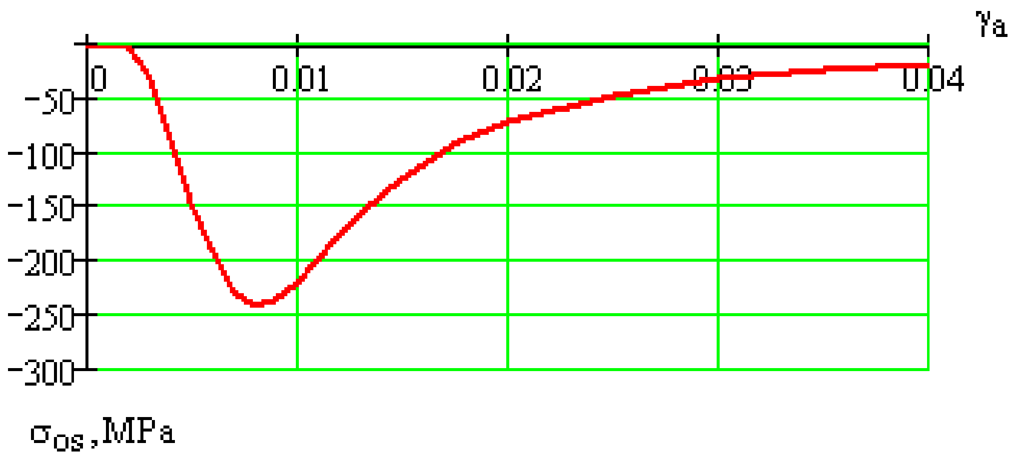

Figure 2. The chart of axial residual stresses on the surface of the product on the amplitude of alternating twisting in case of deformation of a sample made of steel 15Cr2MnMoV in the sequence: stretching up to $\sigma = 0.75 \cdot \sigma_{0.2}$, fixation of reached deformation ε at the constant level, twisting to $\gamma_{max} = \gamma_a$, twisting in the opposite direction to $\gamma_{max} = -\gamma_a$, twisting in the initial direction to $\gamma_{max} = 0.55 \cdot \gamma_a$.

Figure 3 shows dependencies that correspond to strengthening a sample according to the rational method of joint stretching and single twisting, and Figures 4 and 5 - according to the rational method of joint stretching and alternating twisting. The results of sample strengthening that were used directly for further fatigue tests are presented.

Figures 3 and 5 show that when the strengthening methods with single twisting, and methods with alternating twisting are used, rather significant deepness of residual axial compressing stresses is achieved (about 1/3 of the radius from the surface). In both cases strength is ensured in the core (residual tensile stresses do not exceed the permissible value), and the core itself remains elastic. However, in case of strengthening by joint stretching and alternating twisting, residual compressing stresses with two times higher absolute value can be induced on the surface (238 MPa vs. 122 MPa). In this case, because of the third partial stage of twisting, the magnitude of residual tangential stresses becomes minimum. Figure 5 (b) shows that the tangential stresses on the surface are close to zero, and along the radius do not exceed their absolute value of 35 MPa, which is virtually a power less than the magnitude of residual compressing stresses induced in the close-to-surface area. In case of methods of strengthening with single twisting, both residual axial and residual tangential stresses of the same level are induced in the close-to-surface area, which is shown in Figures 3 (c) and (d).

Another tested method of strengthening by joint stretching and alternated twisting with the same amplitude did not reveal any advantages before the existing methods of joint stretching and single twisting.

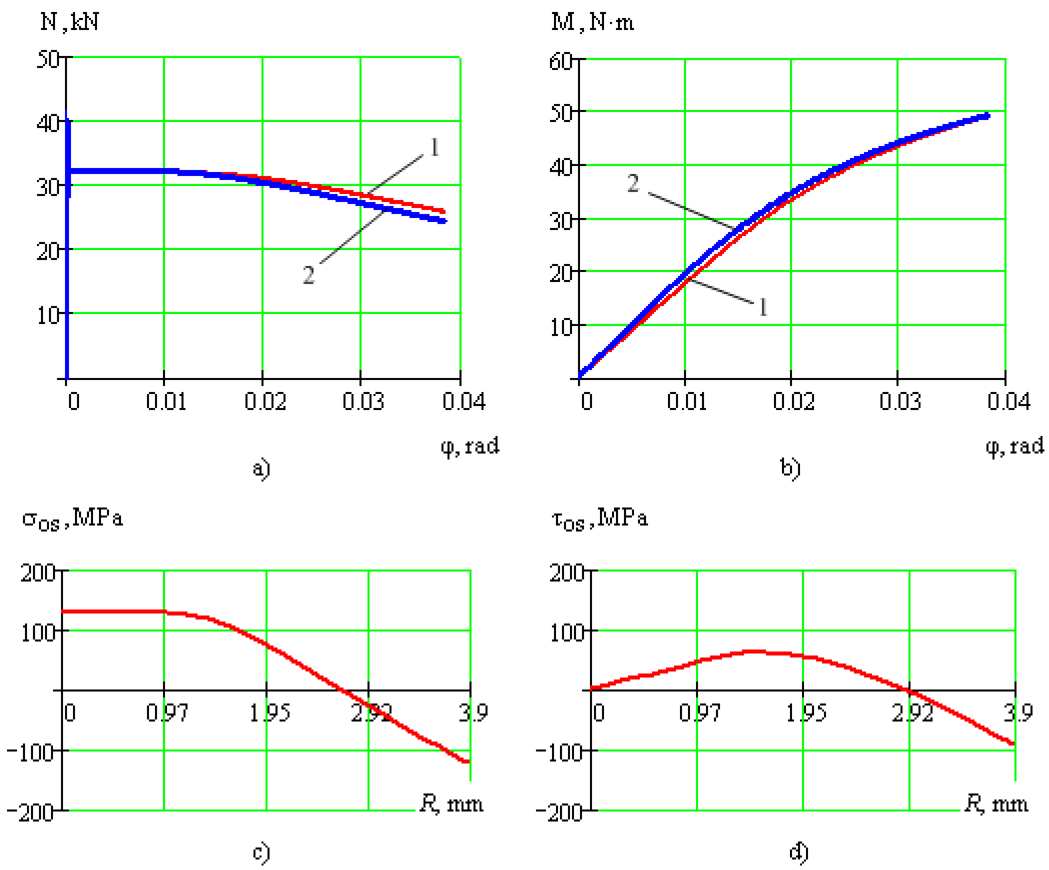

Figure 3. Dependency graphs: (a) longitudinal force, (b) torque from the twist angle; distribution: (c) residual axial, (d) residual shear stresses along the radius of the cross-sectional sample of steel 15Cr2MnMoV when it is strengthened in the following sequence: stretching to $\sigma_{0.2}$, unloading up to $\sigma = 0.75 \cdot \sigma_{0.2}$, fixation of reached deformation ε at the constant level, twisting up to $\phi = 0.038$ rad ($\gamma_{max} = 0.0075$). 1 - model, 2 - experiment.

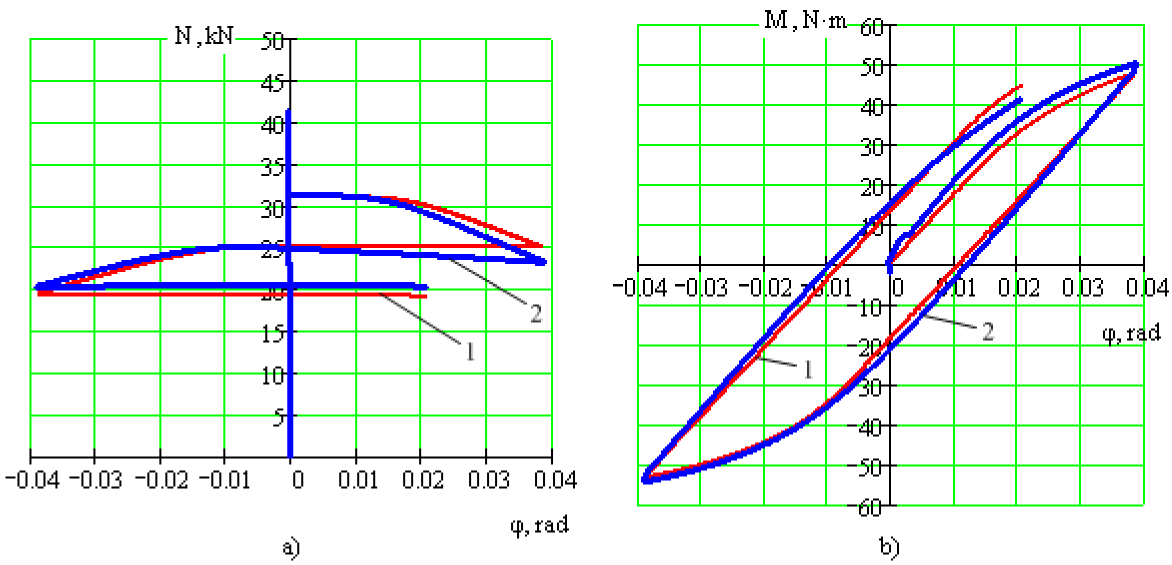

Figure 4. Dependency diagrams: a) longitudinal force, b) torque on the twist angle during strengthening a sample of 15Cr2MnMoV steel in the following sequence: stretching to $\sigma_{0.2}$, unloading up to $\sigma = 0.75 \cdot \sigma_{0.2}$, fixation of reached deformation ε at the constant level, twisting up to $\phi = \phi_a$ ($\phi_a = 0.039$ rad, $\gamma_{max} = 0.0075$), twisting in the opposite direction to $\phi = -\phi_a$, twisting in the original direction until $\phi = 0.021$ rad ($\gamma_{max} = 0.004$). 1 - model, 2 - experiment.

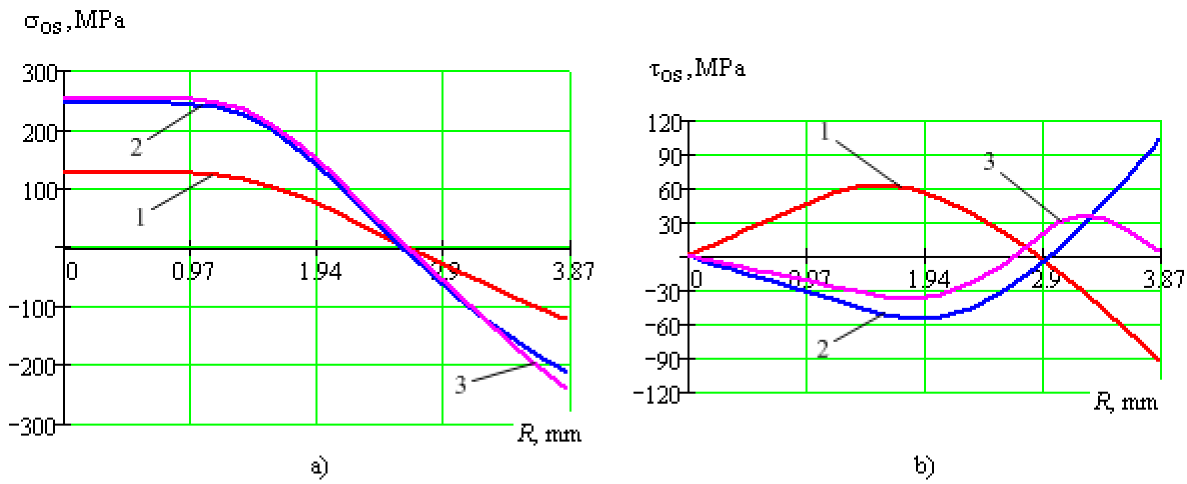

Figure 5. Distribution of residual axial a) and residual shear b) stress along the radius of the cross-sectional sample of 15Cr2MnMoV steel in case of possible full unloading: 1 - first 2 - second 3 - third stage of twisting in case of strengthening in the following sequence: stretching to $\sigma_{0.2}$, unloading up to $\sigma = 0.75 \cdot \sigma_{0.2}$, fixation of reached deformation ε at the constant level, twisting up to $\phi = \phi_a$ (ϕ_a = 0.039 rad, γ_{max} = 0.0075), twisting in the opposite direction to $\phi = -\phi_a$, twisting in the original direction until ϕ = 0.021 rad (γ_{max} = 0.004).

Studying the influence of strengthening by joint stretching and twisting on the corrosion fatigue strength of the item

In the third stage, the influence of strengthening by joint stretching and twisting on corrosion fatigue strength of the item was studied. To do so, multi-cycle corrosion and fatigue tests were performed on three batches of samples: the basic non strengthened batch; the batch strengthened using the rational method of joint stretching and single twisting, and a batch strengthened using the rational method of joint stretching and alternating twisting. The tests were performed in accordance with standards [3], [13] on smooth laboratory samples 8 mm in diameter and a cylindrical working part 20 mm long, according to the sketch shown in Figure 6. All samples were taken from the core of the cylindrical parts of new oil pumping rods made of 15Cr2MnMoV steel. In processing the results of tests, individual sizes of each sample were used with regard to their deviations from the basic ones.

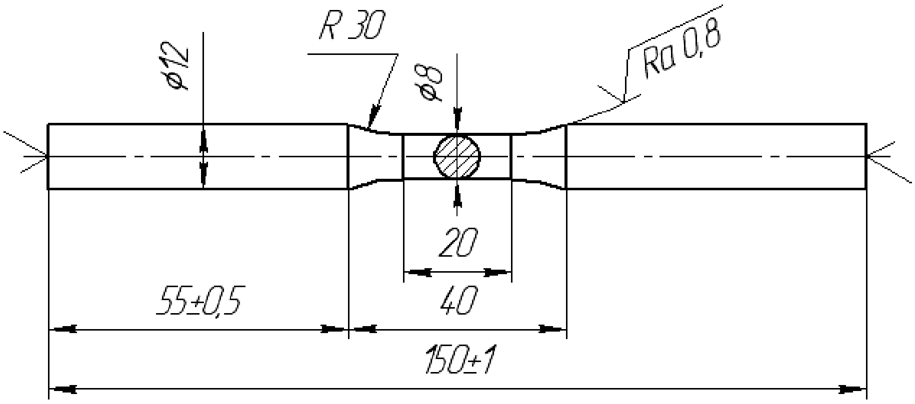

Figure 6. A sketch of fatigued sample.

The samples were strengthened at the Center of Experimental Mechanics of the Perm National Research Polytechnic University on the test system Instron 8850, and the fatigue tests were performed in the laboratory of fatigue strength of the Department of Materials, Technologies and Engineering of the Perm National Research Polytechnic University. Types of tests: cantilever bending of a rotating sample in the medium of 3.5% NaCl solution with symmetrical soft loading with 50 Hz frequency. In order to obtain results of tests in the studied range of longevity (between 10^6 and 10^7 cycles), the strategy of the up-and-down method was used [11].

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The following exponential equation was used for describing the fatigue curve in corrosion environment:

$$N \cdot \sigma_{\max}^{m1} = C, \quad (17)$$

where σ_{max} is the maximum stress level in the cycle, and N is the longevity at the corresponding stress level. The parameters of the fatigue curve C and m1, corresponding to 50% probability of failure, are found from test results using the least squares method. Thus, by introducing an additional assumption about the constancy of coefficient m1 for the entire samples selection, and by relating scattering of the results with variability of only the C parameter, probabilistic diagrams of corrosion fatigue are built. Figure 7 shows corresponding diagrams for failure probabilities 10%, 50% and 90%.

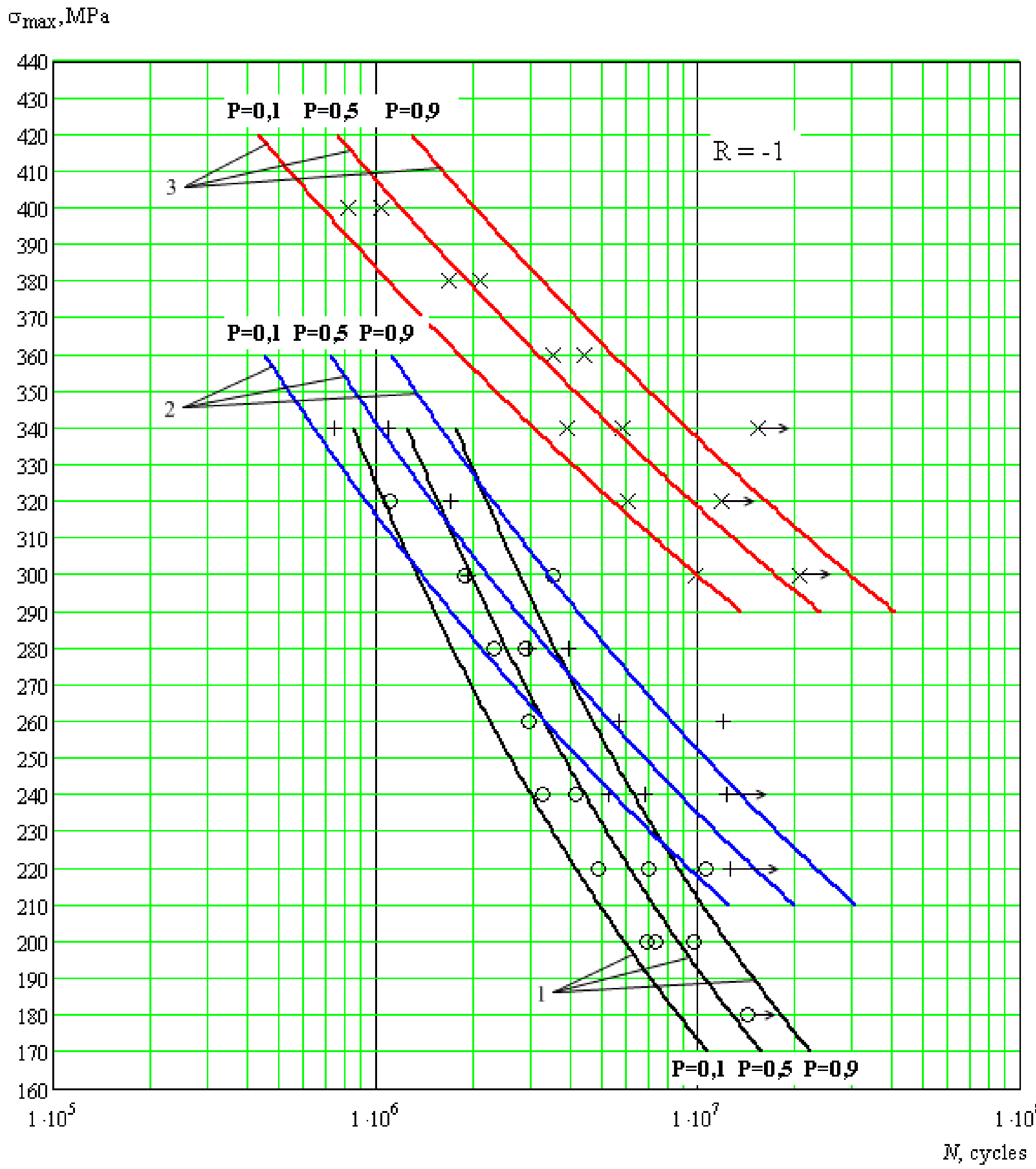

Figure 7. Diagrams of corrosion fatigue built from the results of testing samples made of 15Cr2MnMoV steel in the environment of 3.5% NaCl solution. 1 - diagrams, ○ - experimental points in the non-strengthened batch samples; 2 – diagrams, + - experimental points in the batch samples, strengthened using the rational method of joint stretching and single twisting; 3 - diagrams, × - experimental points in the batch of samples strengthened using the rational method of joint stretching and alternating twisting; P - probability of failure; → - the sample is not destroyed.

For batches of samples not strengthened using the rational method of joint stretching and single twisting, the average probability limit of durability on the base of 10^7 cycles was σ_{-1} = 235.3 MPa with root mean square deviation $S\sigma_{-1}$ = 13.48 MPa. It is 1.22 times higher than the limit of durability for the non-strengthened batch, which is σ_{-1} = 193 MPa with $S\sigma_{-1}$ = 15.08 MPa. Durability corresponding to the 50 % probability of failure with comparable levels of stresses (270 ÷ 210 MPa) increased 1.5 ÷ 2.5 times, compared to the non-strengthened batch. On the contrary, at levels of stress above 330 MPa, i.e., above the level of iron crossing curves 1 and 2, durability decreased.

For batches of samples strengthened using the rational method of joint stretching and alternating twisting, the level of durability was σ_{-1} = 318.8 MPa with $S\sigma_{-1}$ = 14.6 MPa, which is 1.65 times higher than the durability level of the non strengthened samples. Durability corresponding to the 50 % probability of failure on the comparable levels of stresses (330 ÷ 290 MPa) increased 5 ÷ 10.5 times, compared to the non-strengthened batch.

Thus, it has been confirmed that strengthening items using the method of stretching, fixation of achieved longitudinal deformation followed by alternating twisting has higher efficiency, compared to the method that includes stretching, fixation of the achieved longitudinal deformation followed by single twisting.

For items that operate under symmetrical cyclic loading, the notion of reduced stress is introduced, which is the stress under symmetrical loading that ensures the same longevity, as for the given asymmetrical loading. Pumping rods mainly operate under loading in positive terms cycles. In order to forecast the level of durability after strengthening by joint stretching and twisting, on the basis of the criteria of reduced stress accepted for the material of pumping rods [2], the following dependency has been obtained:

$$\sigma_R = \sqrt{\frac{2 \cdot \sigma_{-1}^2}{1-R} + \left(\frac{\sigma_{os}}{2}\right)^2} - \frac{\sigma_{os}}{2} \quad (18)$$

With known magnitude of the residual axial stresses induced in close-to-surface area (σ_{os}), and known σ_{-1} defined for the non-strengthened batch of samples on the base equal to the given durability, using formula (18) one can define the level of durability of the strengthened item on the same base, with coefficients of cycles asymmetry $R = \frac{\sigma_{min}}{\sigma_{max}}$ (σ_R). When comparing with the results of fatigue test, formula (18) ensures higher σ_R value with the relative error equal to 8 ÷ 10 %. This error is acceptable, since the fatigue characteristics themselves are subject to considerable variation.

CONCLUSION

By the whole of the research, the technology of strengthening long cylindrical items has been developed, theoretically justified, and experimentally proven; this technology consists in reverse (alternating) twisting of a preliminarily stretched rod with fixed longitudinal deformation.

A mathematical model of elastic-plastic deformation by joint stretching and twisting of a thin-walled tubular item has been created. By the results of testing of thin-walled tubular samples with highly accurate equipment, material parameters of the mathematical model were found, and its adequacy was proven. Based on the model of deformation of a thin-walled tubular item, a mathematical model of strengthening a homogeneous round cross section rod by stretching and twisting was developed. By results of testing round cross section samples with highly accurate equipment, the adequacy of the mathematical model was proven, and the range of strengthening methods has been established, where it reflects material behavior with the accuracy that is acceptable for practice.

We studied both currently used methods of strengthening that include stretching, fixation of the achieved longitudinal deformation followed by single twisting, and the new methods of strengthening that include stretching and fixation of the achieved longitudinal deformation followed by alternated twisting (with constant or varying amplitudes).

With the help of the built mathematical model, the most rational methods of strengthening for a 15Cr2MnMoV steel rod were defined for each of the studied methods (joint stretching: and single twisting, and alternated twisting with constant amplitude, twisting with varying amplitude). It was found that the developed new technology of strengthening by joint stretching and alternating twisting is much more effective, as compared to the existing method of joint stretching followed by single twisting, and the studied method of joint stretching followed by alternated twisting with constant amplitude.

Comparative corrosion-fatigue bending tests of rotating samples under symmetrical soft loading were performed on three batches of samples: reference (not strengthened); strengthened using the rational method of joint stretching followed by single twisting; and strengthened using the rational method of joint stretching and alternating twisting. Increased characteristics of resistance to corrosion fatigue due to strengthening of a linear round rod by both stretching and twisting have been proven. Higher efficiency of the new developed method of strengthening by stretching an alternating twisting compared to the existing method of strengthening by stretching and single twisting has been proven.

In case of pumping rods, it is necessary to adjust the developed strengthening method with regard to the non-uniformity of distribution of initial mechanical properties along the length of the item. Therefore, the next stage of the research is transferring from a linear homogeneous rod to a rod with non-uniform distribution of mechanical properties along its length, i.e. using the developed method of strengthening by joints stretching and alternated twisting for a natural item, namely, a pumping rod.

The obtained results are being practically tested. The obtained results are planned for implementation at the Perm Oil Machine Engineering Company.

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