Calculation and Justification Parameters of Strengthening Technology to Produce Drill Rig Shaft Gear on the Basis of Mechanics of Technological Inheritance

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Abstract **– Gear shafts of drill rigs in case of holes drilling in coal mines work in complex aperiodical loading conditions. One way to reduce metal consumption of gear shafts is to use the combined strengthening technology on the basis of plastic deformation of the surface (PDS) method. FEM modeling of plastic deformation of the surface process and calculations of stress and strain state were done. It is shown that due to combined strengthening the yield points, stress limit and fatigue limit increase; these factors allow performing stress and fatigue crack life calculations in case of gear shafts mass is decreasing on 10-10%. It is estimated that in case of metal consumption decrease not less than in 1,5-2 times the necessary factors of safety and fatigue crack life are provided.**

Keywords – drilling machine, metal consumption, plastic deformation of the surface, static strength, fatigue crack life

I. INTRODUCTION

One of the main reasons of low technical-and-economical indexes of drilling operations in coal mines is low technical level of used drilling equipment. For a long time engineering policy in crea-tion of new drilling rigs was oriented only on further modernization of existing constructions, but not on essential quality improvements. Technology of drill rigs production was not also improved. Drilling equipment development in the direction of its power available per work increase doesn't lead to proper drilling productive capacity increase. It can be explained by the absence of rational balance of drill rig parameters. Disfunction of appropriate correspondence of rig drive power to it weight, stem length and size influence operational features of drill rigs significantly. As experience of drill rigs of BGA type creation shows, engineering solutions don't promote feelable technical level increase without technical process of rigs production improvements.

The analysis showed that for example: a gear shaft of a driver of a drill rig of BGA-2M type, made by "Angeromash", has significant (to 20 times and more) factor of safety on static loads and fatigue limit that further leads to high metal consumption of these machine parts. Furthermore, en-gineering measures to increase technical level of a drill rig don't allow providing decrease of rig mass without improvement of its parts production technology [1-2].

N.M. Skorniakov and I.N. Gergal stated that highly dynamic character of actual load is not con-sidered when a rotary driver of a drill rig is being developed and calculated. The dynamic character of a rotary driver of a drill rig, which is described by the system of nonlinear differential equation, allows estimating authoritative values and character of load, influencing the gear elements. Also it was found that rotary driver elements of a drill rig are in extremal conditions of loading (dynamic constituent of load reaches 55% of static one). The character of sharing of rotational power was stated, and also it was estimated that its maximal values are on the second gear shaft (shaft №2) un-der short (<6 m) drilling assembly and reach 6000 H*m (fig. 1). With the increase of length of drill-ing assembly maximal values of rotational power are decreasing smoothly to 4000 H*m with length of 90m.

As it is known, static and fatigue strength in their turn are largely depend on the quality of ma-chine part surface coat, defined by surface roughness, strengthening and residual stress. Therefore, technological inheritance must be taken into account in the design processes of critical machine parts manufacturing, technological inheritance is defined as transference of properties of the surface layer from the previous operation to the following ones.

This is especially relevant for the use of strengthening processing techniques, which should provide rational combination of strengthening and residual stresses. This is possible through the use of modern concepts of physical and mechanical processes of deformation and destruction of structural materials.

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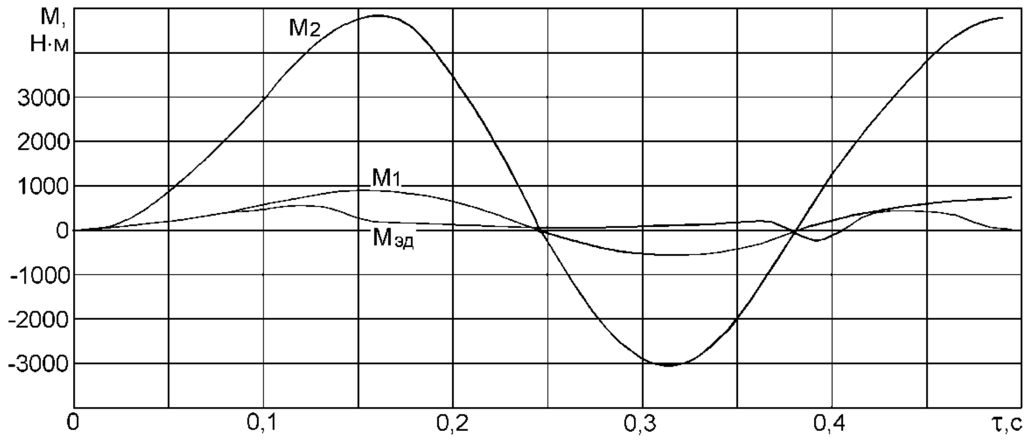


Fig.1. Changes of rotational power in elements of rotary actuator under its fixing (length of drilling assembly L = 24 m): M_1 – the first gear shaft; M_2 – the second gear shaft; M_{em} – the electric motor

Throughout this work the scientific and practical task of metal consumption (mass) reduction and increase of quality of machine parts of a drill rig BGA-2M type was solved, by means of its parts (gear shaft) mechanical properties increasing through the creation of more improved technology for their manufacture.

II. Materials and methods

Among the main problems to provide strength while creating machines are: the occurrence of sudden failures of machine parts; providing certain factor of safety as excessive strength increases machine cost and its weight; lack of durability, which increases operating costs; increased time and high costs for development of newly build machines to improve their reliability [3-4].

To a large extent, these problems are solved by using steel material of particular quality. If in re-sult of theoretical and experimental studies loadings, acting on its units and parts, were determined with high precision, then the tasks of reliability are solved by using certain parts of steel for machine parts and by related strengthening technologies during parts manufacturing.

Thus, the effective direction of the direct metal economy is to reduce the real (in some cases un-justified) factor of safety of machine parts by clarifying diagrams and calculation methods, operat-ing conditions, i.e. approaching of design loads to real ones.

The task of reducing the cross-sections of parts while providing a specified period of operation and reliability is solved by the calculations of machine elements for durability under application of static and cyclic loads. Indirect savings give the effect by means of changing the design characteris-tics, current operational loads account, the usage of strengthening technology and others. The effect of these activities is to increase the durability of products, relative contraction in output and is im-plemented gradually, according to machine operation.

Under the current production the typical processing technology of shaft-pinion No2 of a gear drill rig, made of steel 20Ch2Ni4A, includes (fig. 2): a group of turning operations; operation of teeth cutting; surface thermo-chemical treatment – cyanidation and high induction hardening (HIH); grinding.

Cyanide layer of depth h = 0.9 ... 1.3 mm after high induction hardening has high hardness 59 ... 63 HRC and high operation features – durability and fatigue limit. In general, accepted technology provides the required quality of the surface layer on the enterprise. However, after the thermal-chemical operations together with the subsequent grinding of the surface layer, residual tensile stresses occur. Under the combined action in the surface layer of residual tensile stresses with operation stresses the positive effect in regard to the fatigue life reduces significantly.

There is no universal method to strengthening machine parts, since one and the same method in the same operation conditions can have a positive effect, and in other conditions – negative one. Therefore, in some cases the combined strengthening of parts is used, based on the application of two or three strengthening methods, each of which allows enhancing this or that operational property. For example, the performance of the surface thermal or thermal-chemical treatment with subsequent surface plastic deformation (PDS) allows to maintain the positive properties of thermal treatment with simultaneous roughness reduction, increasing strength limits and yield point as well as fatigue point (through the creation of press residual stress). The PDS method is rather simple to implement, it does not require expensive equipment and allows at the same time to obtain the desired quality indexes of the surfaces layer for various parts in operating conditions. The most wide spread methods are methods of rolling by a ball and a roller and smoothing. Processing by PDS method is possible for most known cast irons, steels, non-ferrous alloys, and it provides: positive micro structural changes in the surface layer of a metal, creating a directed texture; high strengthening effect, calculated by increased

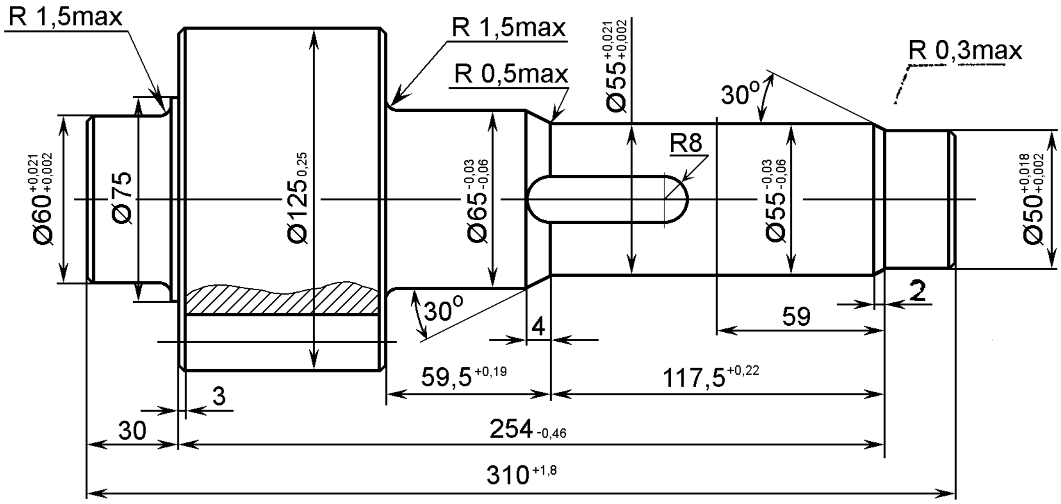


Fig. 2. Shaft-pinion of gear drilling rig of BGA-2M type

hardness of the material on 20-60% or more, when the depth of plastic deformation expansion is 0.01-10 mm; creation of compressive residual stress in the surface layer; obtaining favorable in shape and minimal in height parameters of roughness of the surface of the range Ra 0.05 ... 1.6 [5-7].

When the research was being done the developed approach to solve the problems of mechanics of technological inheritance was used by the authors [7].

The analytical tasks were formulated and solved to define strain-stress state (SSS) and estimation of accumulated mechanical properties of the surface layer for the samples in their initial state after the strengthening by PDS method and after combined strengthening, including nitriding, hardening and PDS.

As model materials steels 40Ch, 40ChNi and 12ChNi3A were used, having properties that are comparable with the properties of steel 20Ch2Ni4A.

Cylindrical samples were fabricated from these materials; the samples have a diameter *Ds*=32; 60; 115.5 mm with limit deviations ±0.5 mm. Three journals were done on each sample with length *l*=80±0.5 mm, separated by each other by lug grooves for the tool output during processing and samples cutting during the study of hardness, micro hardness, microstructure and etc.

The samples in the initial state and after hardening were processed on a turning machine on finishing modes with lubricating and cooling liquid.

Samples of the first series were processed according to manufacturing technology without subsequent thermal treatment, and samples of the second series were additionally subjected to cyanidation and high induction hardening. Samples of both series later were treated by PDS method by one roller tool with diameter *Dr*=95 mm with a profile radius *Rpr*=2.0; 2.5; 5.0 mm.

Rolling modes of unhardened samples by one roller tool: frequency *n*=13.3 c^(-1), feed *S*=0.1…0.26 mm/t and rolling force *P*=1000…4000 H:

• steel 40Ch; samples diameter *Ds*=32 mm; total 18 samples;

• steel 40ChNi; samples diameter *Ds*=115.5 mm; total 20 samples;

• steel 12ChNi 3A; samples diameter *Ds*=60 mm; total 18 samples.

Rolling modes of untempered samples by one roller tool: frequency *n*=10.5 c^(-1), feed *S*=0.07 mm/t and force *P*=1950…4550 H:

• steel 40Ch; samples diameter *Ds*=30 mm; total 18 samples;

• steel 40ChNi; samples diameter *Ds*=105 mm; total 15 samples;

• steel 12ChNi 3A; samples diameter *Ds*=50 mm; total 5 samples.

At the stage of steady-state process after surface plastic deformation treatment on the length of 15-20 mm to fix the deformation zone boundaries the quick return movement ("shooting") of a deforming tool – a roller from the treated surface of the sample was performed.

The recordings of profilograms of contours were done; contours were obtained of deformation zone with the subsequent processing of these profilograms according to special algorithm and determination of geometric parameters DZ [8].

III. Results

For example for further modeling and further comparative analysis, 40Ch steel samples were chosen; the samples were processed by PDS method under similar modes:

№ 132, unhardened; feed S=0.1 mm/t; rolling force P=4000 H; profile radius *Rpr*=2.0 mm;

№ 131, hardened; feed S=0.07 mm/t; rolling force P=3900 H; profile radius *Rpr*=2.0 mm.

By means of the method of hardness measurement according to Vickers the parameters of the surface layer strengthening have been established, which are the following: strengthening depth h=2.8 mm and h=1.2 mm, the degree of strengthening δ=0.24 and δ=0.14 for nonhardened and hardened samples respectively.

According to the geometric parameters of the deformation zone, hardening parameters and mechanical properties (hardness, flow curve, etc.) initial and boundary properties have been formed to solve the problems of estimation of stress-strain state. The design scheme has been drawn up, in which the material was taken in elasto-plastic state, and the problem corresponds the notion of plane deformation condition.

The PDS scheme process is seen in the axial section of the shaft, in which the plane of principal deformations is placed (fig. 3).

On the deformation zone profile, obtained by profilograms method, the following specific points are highlighted – the lines in zone: h_{at} – actual roller tightness, equal to the tool indention depth; h_w– elastic-plastic wave height in front of deforming tool; $h_r=h_{at}+h_w$ – rated roller tightness, equal to the front contact arc vertical projection; Δ – elastic-plastic metal recovery height behind the deforming tool; d – front contact arc horizontal projection (deformation zone front contact length); d_1 - back contact arc horizontal projection (deformation zone back contact length); l – wavelength in front of deforming tool (deformation zone front non-contact part length); $L=l+d$ – deformation zone front part length; l_1 – deformation zone secondary part length.

Along the profile of the deformation zone plastic

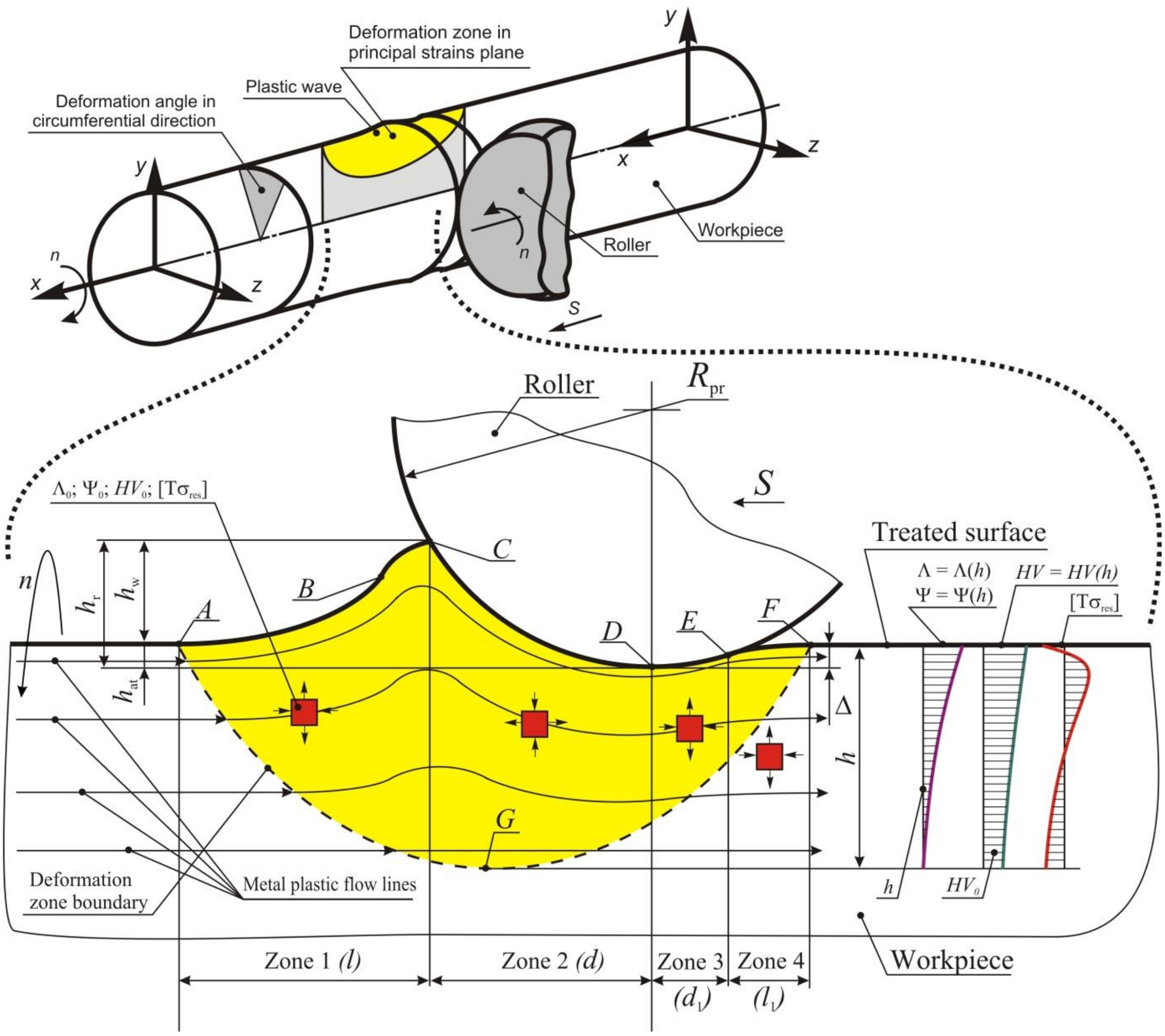


Fig. 3. The PDS scheme process

deformation arises at the point A and ends at point F. The profile of the deformation zone consists of the front non-contact ABC area, the contact area CDE and the rear non-contact EF area. The front non-contact area, in its turn, consists of the concave area AB and the convex area BC.

When the surface layer is loading the material particles move in deformation zone along the current flow lines 1,2 and 3, the plastic deformation extends to the depth h, whereby the surface layer is formed with irregular in depth of shear strain level, plasticity reserve exhaustion level of and residual stress tensor.

The problem of calculation of stress-strain deformation state was solved using the finite element method (FEM) in accordance with the algorithm and computer program [9-10]. In the elasto-plastic body ABCDEF with fixed lower boundary the perfectly rigid indenter was implemented – a roller with radius *Rpr*. The indenter was displaced on range of S feed along the x-axis; while moving along axis y was absent.

Input data to create a model of the material were: Young's modulus E=2·10^(5) MPa, the density of the material ρ=7800 kg/m^3, the Poisson's ratio ν=0,3 and the flow curve of material [11-12] . The strain-stress state calculation in the elasto-plastic formulation assumed idealization of the flow curve by splitting into two rectilinear areas: area of elastic and plastic deformation. This allows describing by three parameters: Young's modulus E, extrapolated yield point σ_f and by a tangential moduleTanMod .

The modeling was performed by varying the parameters of the material, the friction coefficient, the indenter movements' charts and other. As a result, the friction coefficient was adopted f=0,21, corresponding operational recommendations [6]. As a result of calculations in units of finite element model numerical values of stresses tensor components were obtained σ_x,σ_y,σ_z,σ_xy, relative deformations ε_x,ε_y,ε_xy and others. As a result of the calculations the number of values of the stresses tensor components was received in the units of finite element model, relative deformations and others.

Subsequently, the obtained values of the stresses components tensor and the deformations tensor in the units of the finite element model were recalculated in the point of the current line of deformation zone (fig. 3). Thus, under the current lines a family of lines is understood, whose tangent lines are congruent at each point in the same time with the direction of the velocity vector to that point. The calculation parameters were performed, including [12-17]:

- stress intensity σ_i and deformation ε_i;
- tangential stress intensity T;
- tensor component of deformation velocity ξ_{ij};
- velocity intensity of strain level H;
- shear strain level for the deformation period t

$$\Lambda = \int_0^t \mathrm{H}(\tau)d\tau; \qquad (1)$$

- mean stress σ;
- scheme index of stress state:

$$\Pi=\sigma/T; \qquad (2)$$

- view index of stress state (Loder-Nadai index) for estimation of nonmonotonicity of deformation progress.

The calculation of the plasticity reserve exhaustion level was performed by the criterion of Cal-pin-Filippov [18-19]:

$$\Psi = \Psi_1 + \Psi_2 = \Psi_1 + (\Psi_{21} + \Psi_{22}) = n\varphi_0 \int_0^{\Lambda_k} \Lambda_i^{n-1} d\Lambda + \left(\int_0^{\Lambda_k} \frac{d\Lambda}{\Lambda_p} - \varphi_0 \int_0^{\Lambda_k} \Lambda_p^{n-1} d\Lambda \right), \qquad (3)$$

where Ψ_1 – constituent, depending on the yield stress or on the accumulated deformation; - Ψ_2– constituent, which depends on the plasticity of metal in Π=const ; Λ and Λ_p - cumulative and limit shear strain level at this index of stress state scheme Π; *n* – deformation strengthening coefficient; φ_0 – coefficient, determined on the bases of plasticity test. The nonhardenable metal Ψ=0, but in full depletion of the plasticity reserve Ψ=1.

As the metal characteristics the hardening curve plasticity diagram were used as $\Lambda_p=\Lambda_p$ (Π).

Residual stress tensor of roller run-samples was carried out in accordance with the theorem of unloading, taking into account the accumulated plastic strain [6, 20]:

$$[\mathrm{T}\sigma_{rs}]_{ij} = [\mathrm{T}\sigma_d]_{ij} + [\mathrm{T}\sigma_{un}]_{ij} + [\mathrm{T}\sigma_t]_{ij} \quad (4)$$

where $[\mathrm{T}\sigma_d]_{ij}$ – load stress tensor; $[\mathrm{T}\sigma_{un}]_{ij}$ – unloading stress tensor; $[\mathrm{T}\sigma_t]_{ij}$ – thermal stress tensor.

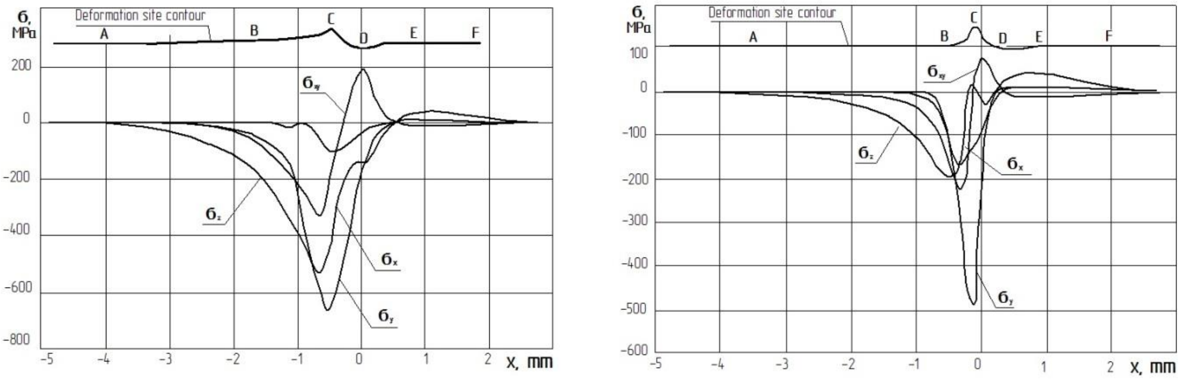
The analysis showed that the processing by PDS according to similar modes:

• in the unhardened sample № 132 plastic deformation is localized in the large volume of deformation zone;

• the intensity of the stresses in the deformation zone of the hardened sample № 131 is about twice as high as the intensity of the stresses of unhardened sample;

• the average normal stress in the deformation zone of the hardened sample is also about twice as high as of the unhardened sample;

• the intensity of deformation in local zones of deformation zone of the hardened sample is higher than that of the unhardened one.



a) b)

Fig. 4. Sharing of stresses component in deformation zone: a) the unhardened sample №132; b) the hardened sample №131

In the process of surface plastic deformation of the sample pattern of the distribution parameters of the stress-strain state is significantly complex (fig. 4-6, along the 1st flow line).

In the deformation zone along the first flow line of the stress tensor components vary from zero values at the entrance to the lowest negative values in the area of plastic wave peaks (C point in fig. 4, a, b). Further movement of a particle along the flow line occurs under increasing stress components under and behind the tool. As the surface layer moves in depth, the character and the absolute value of the stress state component vary. In general, the absolute values are reduced; component σ_y remains maximal.

This way of distribution of stresses leads to the fact that most of the material of the deformation zone is under contractional setting, with the highest value of the average normal stress corresponds to the contact area of the tool with a part (fig. 5, a, b). The greatest values of intensity of tangential stresses occur in the area of the top of the wave in front of the deforming tool. When the surface layer moves in depth there is decrease of the absolute values, but the nature of the distribution of these components remains practically unchanged.

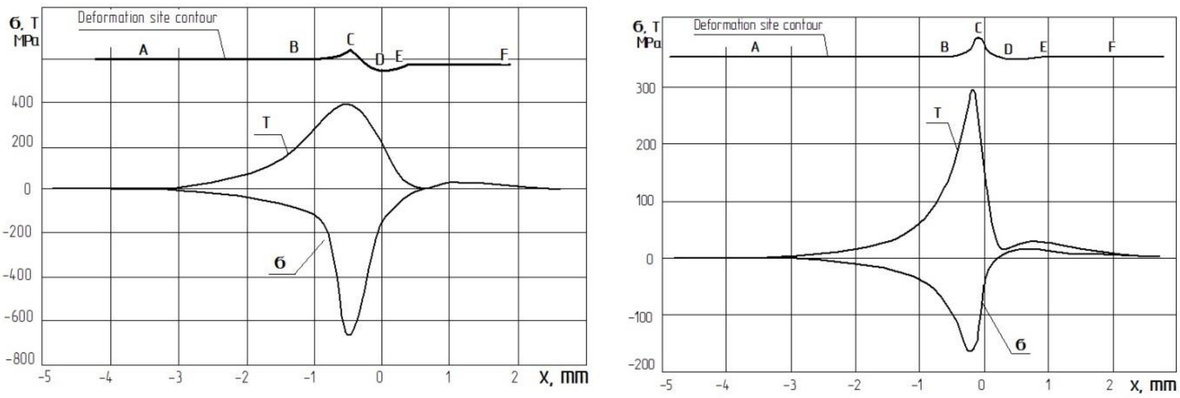
The picture of the deformation rate sharing is complex (fig. 6, a, b).

Based on the nature of strain stress state it was established that in plastic deformation zone there are 3 sections of quasimonotone deformation, the deformation changes its sign at the boundaries of sections. The first section is placed from the entry point in the deformation zone to the point near the top of a wave; the second section is under the tool, and the third one is behind the tool.

Among the features of the stress strain state under PDS of the sample № 131 from hardened steel in comparison with the sample №132 from unhardened steel it should be included:

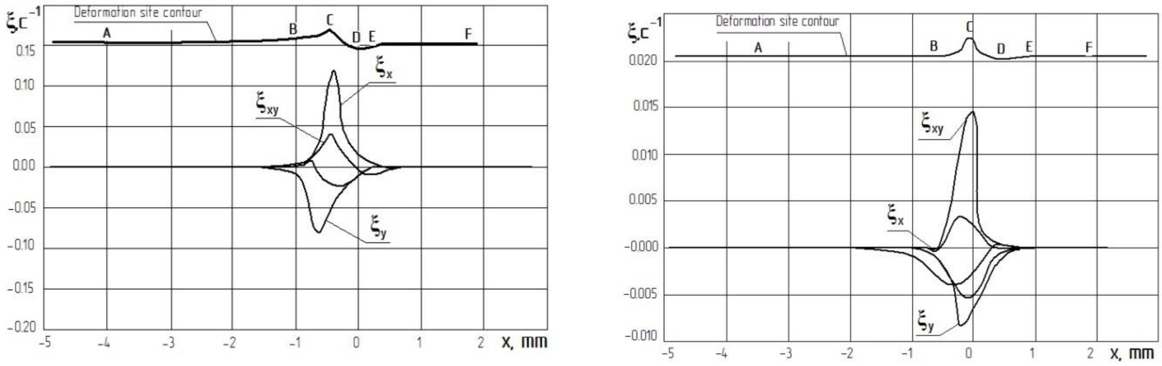
• significant size reduction in the deformation zone;

• reduction of the numerical values of the stresses component and localization of velocities growth of strain shear in the area of plastic wave peaks before the deforming



a) b)

Fig. 5. Sharing of medium direct stress and the intensity of tangential stress in deformation zone: a) the unhardened sample №132; b) the hardened sample №131



a) b)

Fig. 6. Sharing of component of deformations velocity in deformation zone: a) the unhardened sample №132; b) the hardened sample №131

tool;

• reduction of the numerical values of the average normal stress and the index increase of the stress state of the circuit.

The calculation of the shear strain level accumulation Λ and the level of Ψ reserve plasticity exhaustion was performed by adding increments of these parameters along the flow lines (fig. 7). It is seen that the most intensive accumulation of strain and exhaustion of the reserve of plasticity occurs in front of noncontact area of the deformation zone.

Distribution of the shear strain level and the plasticity reserve exhaustion level (PREL) on the depth of the hardened surface layer has recessive nature, with the largest part of the shear strain and the plasticity reserve exhaustion level is localized in the surface layer up to a depth of 0.6 mm (fig. 8). In this layer up to 50-60% of the total deformation accumulates, and by about 35-40% metal plasticity level is exhausted. The shear strain level obtained experimentally by measuring the Vickers hardness, confirms the validity of the analyzing results.

The calculations and experimental studies have shown that after treating by PDS of unhardened material the increase in yield stress point was noticed from 550 to 650 MPa (18%) and for the hardened material it was from 800 to 1000 MPa (by 25%). Increased stress limit and fatigue limit was 15 and 25%, respectively for unhardened and hardened steels.

The indicated values of the mechanical properties after PDS treatment were used in problems of calculation of static strength and cyclical durability of hardened PDS parts.

The calculations were performed by standard methods using actual values acting on the shaft loads. Loads in the form of torque and rotational moment were taken according to the received analytical solutions [1-2]. Tensor of current (total) aperiodic stresses $T\sigma_e$ under the calculations of cycle life durability was presented as a sum of tensors of residual $T\sigma_r$ and fatigue (cyclic) stresses $T\sigma_f$ [7]:

$$T\sigma_e = [T\sigma_{rs}]_{ij} + [T\sigma_f]_{ij} . \tag{8}$$

As the example the complex nature of the sharing

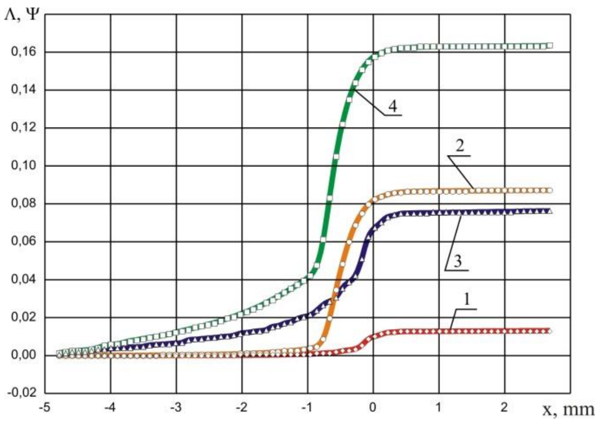


Fig. 7. Accumulation of deformation properties along the 1st flow line in deformation zone: 1 and 2 – shear strain level Λ in samples №131 and 132;
3 and 4 – the plasticity reserve exhaustion level Ψ in samples №131 и 132

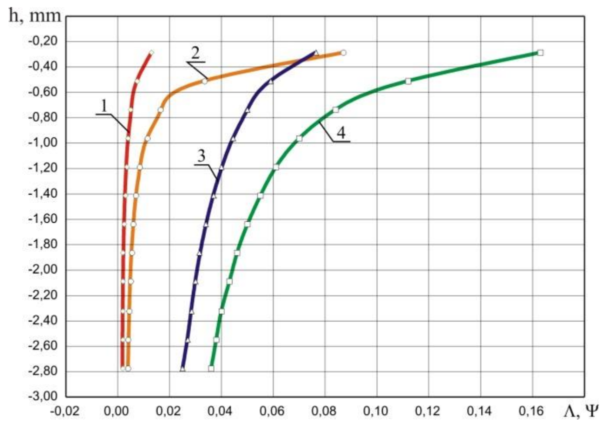


Fig. 8. Sharing of accumulated deformation properties on the hardened layer depth: 1 и 2 – shear strain level Λ in samples №131 и 132;
3 и 4 – the plasticity reserve exhaustion level Ψ in samples №131 и 132

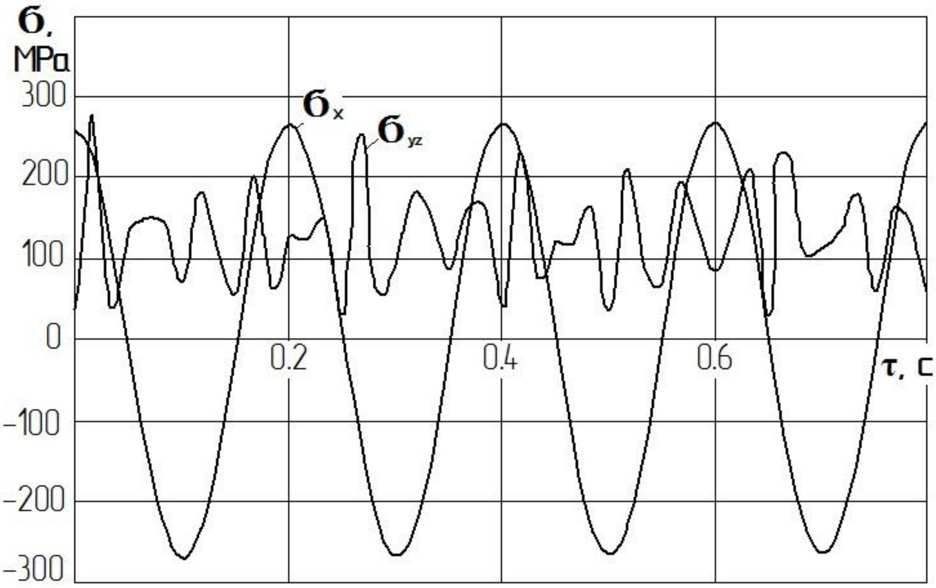


Fig. 9. Stresses in dangerous section under diameter reduction in 30% (the section diameter is 45.5 mm)

component σ_x and σ_yz of operating stresses tensor is shown in fig. 9.

It is stated that the cyclic durability of the pinion-shaft after cyanidation, quenching and PDS is 33,500,000 cycles that is in 7.5 times larger than durability predetermined by technical requirements. Such increase in fatigue strength characteristics allows reducing the diameters of the pinion-shafts and, therefore, reducing metal consumption of gear of a drilling machine.

Further calculations were carried out by reducing the diameter by 10%, 20% and 30%. The cross section in which the maximum stresses occur (diameter 65 mm, fig. 2) has a diameter of 58.5 mm, 52 mm and 45.5 mm respectively.

IV. Conclusions

The analysis of the modeling results, experimental studies and calculations of factor of safety coefficients for reducing the diameter of the shaft necks on №2 in (10-30) % showed that:

coefficients of the factor of safety on the yield point while bending is reduced in 2 times, remaining, however, at a high level within $29.3 \ll n_{\sigma} \ll 69.2$;

safety factors on the yield point under rotation also reduced about 2 times, remaining, however, at a high level within $11.4 \leq n_{\tau} \leq 77.0$;

final safety factors of static strength of the shaft necks are reduced about 2 times and form $9.9 \leq n \leq 49.9$;

coefficients of the fatigue limit under the influence of the nominal bending unbalanced loads are $136.9 \leq n_{\sigma\_(-1)} \leq 437.5$;

coefficients of the fatigue limit under the influence of the nominal bending unbalanced loads from the asymmetric torque are $143.9 \leq n_{\tau\_(-1)} \leq 890.5$;

final coefficients of safety factors for fatigue limit under the combined action of the torque and bending moments are $119.4 \leq n \leq 392.7$.

Thus, the application of combined processing by PDS method of cyanidation and hardened steel allows reducing metal consumption of a pinion-shaft at least in 1.5-2 times, while ensuring an adequate safety factor and cycle durability.

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