

Finite Element Modeling of Strengthening Process by Means of Surface Plastic Deformation Using a Multiradius Tool

Valeriy Yu Blumenstein, Maksim S Mahalov, Anastasia G Shirokolobova

T. F. Gorbachev Kuzbass State Technical University,
28, Vesennyaya St. 650000, Kemerovo, the Russian Federation

E-mail: blumenstein@rambler.ru

Abstract: New designs of deforming tools with a complex working profile, based on the mechanics of technological inheritance, have been developed. The finite element method modeling of the surface plastic deformation process by a multiradius roller was performed and possibility to accumulate large values of deformation without destroying the metal of the surface layer was shown.

Introduction

In modern machine building, constant attention is paid to improving the schemes and methods of machining. Serious attention is given to increasing the accuracy of processing and the quality of the surface layer of machine parts. Today, there is no doubt that the quality of the product is laid in at the stage of design. This involves transferring of the product creation from full-scale testing of prototypes or batches to mathematical modeling of product properties, as well as modeling of product manufacturing process, which allows detecting and eliminating design and technological faults before the production stage begins.

The development of new tools and technologies is based, first of all, on the modeling of machining processes. Modern finite-element program products allow the development of high-quality models and their comparison with experimental tests proves it.

Thus, new achievements in hard metals mechanical processing based on physics of modeling are presented in the paper [1]. The authors show that the reduction in the cycle time and providing quality assurance depends on the physical model activity for hard metal processing.

Knowing physical laws of metal plastic flow allowed to develop and successfully apply the cutting processes with advanced plastic deformation (APD) [2]. The effectiveness of the APD method is achieved by the purposeful change in physico-mechanical properties of material of the cut-off layer by its preliminary deformation, which is carried out in the process of cutting by additional mechanical energy source.

Calculations of the stress-strain state and evaluation of ductility in the deformation zone allowed to improve the deforming-cutting pulling (DCP) scheme with advanced plastic deformation [3]. To eliminate the elastic shrinkage of the product (bush) a number of deforming-cutting and pulling ways were developed with the combination of cutting and deformation zones with the cutting edges in the zone of contact deformation. This allowed to reduce the energy consumption of the cutting process by 20% compared with the deforming-cutting pulling with the APD, as well as the total energy costs of cutting and deformation by 10-14%.



The development of methods and technologies of SPD is associated with the refinement of FEM models, complication of deforming tools geometry, imposition of thermal and vibration effects, consideration of metal plasticity and so on.

So, for example, Yu.I. Sidyakin and his co-authors carry out scientific researches, engineering calculations and design the SPD processes by modeling the contact interaction of the indenter with the processing material and with evaluation the elastoplastic deformation [4].

In the research area of S.A. Zaides the processes of cross-sectional SPD are investigated and developed, allowing to ensure the accuracy and high quality of the surface layer of the parts [5]. In the elastoplastic putting the FEM model of the process was developed, calculations of the stress-strain state of the deformation center were performed. Mathematical modeling and subsequent engineering calculations made it possible to create a theory of the process, to develop technological recommendations and a set of technological equipment that provides specified values of accuracy, hardening and residual stresses based on the assigned operating conditions of the slightly hard axel.

T. Altan carried out a study of the mechanics of the SPD process, creating 2D and 3D FEM models of rolling-off by a roller [6]. The results of modeling, including surface deformations and residual stresses, have showed high convergence with experimental data, obtained from literature sources.

V.M. Smelyansky developed a mechanical theory of SPD process, the stress-deformation state modeling of the deformation zone was carried out and the rules of formation of the surface layer of machine parts were established. It was established that the asymmetric deformation zone (DZ) arises under the SPD processing, the shape and size of which depends on technological factors [7]. The motion of a metal particle in the DZ is carried out along the current flow line, taken at a certain depth and determined according to the tasks solution of the mechanics of rigid body. Moving along the current flow line, equidistant to the deformation zone, the particle passes through three states: initial, current and final. The model analysis made it possible to obtain the distribution of stress tensor components, deformations and rates and allowed to evaluate the effect of hydrostatic pressure on the accumulation of deformation and the exhaustion of the reserve of plasticity of metal.

One of the important trends in the development of machining technologies, including SPD, is the creation of nanostructured state in a thin surface layer of the metal.

A.V. Kirichek and D.L. Soloviev developed a method of gradient static-impulse processing (SIP) of SPD on the basis of the physical model, using shock waves for plastic deformation, creating high pressure in the deformation zone and forming great depth of the hardened surface layer [8]. Crushed metal particles measuring up to 100 ... 300 nm have been revealed in the hardened sample; great concentration of nanoparticles was found in the surface layer at the depth of 3 ... 8 mm. The authors showed that the method of deformation hardening by shock waves makes it possible to create heterogeneous ultrafine-grained gradient-hardened structures, alternating solid and plastic zones according to the given law.

In dynamic FEM modeling V.P. Kuznetsov and co-authors performed the process of smoothing out a thin surface layer of a steel sample under the indenter, introduced with constant force and with constant speed [9]. Under the conditions of plane deformation, the regularities of changes in the stress-strain state (SSS) of the material and the mechanisms of the nanostructured layer formation have been studied. The results of the studies are in good agreement with the experimental data.

One of the priority areas is the development and implementation of intensive plastic deformation (IPD) methods, the feature of which is high hydrostatic pressure in the deformation zone [10-11]. This allows to achieve high plastic deformations, to provide a nanostructured state without destroying the metal, and, as a result, to achieve a unique combination of high strength and ductility at room temperature.

It is known that the action of the cutting and / or deforming tool on the nanostructured metal of the surface layer leads to plastic and thermal deformations, which lead to grain growth and loss of most useful properties. Therefore, the efforts of researchers are also aimed at preserving these properties, including the determination of rational regimes of mechanical processing [12].

The analysis showed that increase in the efficiency (intensification) of the processes of "cold" mechanical hardening treatment is possible by creating complex stress-strain state with predominantly high hydrostatic pressure in deformation zone. In turn, such schemes are realized by tools with complex geometry and which provide a certain kinematics of the metal flow.

Theoretical investigations

The author has developed the theory of formation and transformation of the inherited state of the surface layer in the processing and exploitation processes – the mechanic of technological inheritance (TI) [13]. The description is based on the idea of continuous accumulation of deformations and depletion of the metal plasticity reserve in the surface layer of the part under the influence of loading programs. The life cycle is represented by the stages of cutting, surface plastic deformation and fatigue loading, which in turn consists of two stages – cyclic durability and cyclic crack resistance.

To solve the problems of the TI mechanics, the parameters known from the mechanics of a deformable solid are used:

- stress condition scheme index:

$$\Pi = \frac{\sigma}{T} = \frac{1/3(\sigma_1 + \sigma_2 + \sigma_3)}{1/\sqrt{6}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}}; \quad (1)$$

- accumulative shear strain level:

$$\Lambda = \left\langle \frac{2}{\sqrt{3}} \int_0^t \sqrt{\frac{1}{2}[(\xi_x - \xi_y)^2 + (\xi_y - \xi_z)^2 + (\xi_z - \xi_x)^2] + \frac{3}{4}(\eta_{xy}^2 + \eta_{yz}^2 + \eta_{zx}^2)} dt \right\rangle; \quad (2)$$

- residual stresses tensor:

$$[T\sigma_{residual}]_{ij} = [T\sigma_{def}]_{ij} + [T\sigma_{unload}]_{ij} + [T\sigma_t]_{ij}; \quad (3)$$

- plasticity reserve exhaustion level [14]:

$$\begin{aligned} \Psi &= \Psi_1 + \Psi_2 = \Psi_1 + (\Psi_{21} + \Psi_{22}) = \\ &= n\varphi_0 \int_0^{\Lambda_k} \Lambda_i^{n-1} d\Lambda + \left(\int_0^{\Lambda_k} \frac{d\Lambda}{\Lambda_p} - \varphi_0 \int_0^{\Lambda_k} \Lambda_p^{n-1} d\Lambda \right), \end{aligned} \quad (4)$$

where σ – average normal stress; T – intensity of shear stress; $\sigma_1, \sigma_2, \sigma_3$ – the main components of stresses tensor; $\xi_x, \xi_y, \xi_z, \eta_{xy}, \eta_{yz}, \eta_{zx}$ – components of strain rate tensor; $[T\sigma_{def}]_{ij}$ – load stress tensor; $[T\sigma_{unload}]_{ij}$ – unload stress tensor; $[T\sigma_t]_{ij}$ – heat stress tensor; Ψ_1 – component, depending on the yield stress or on the accumulated deformation; Ψ_2 – component, depending on metal plasticity in conditions $\Pi = const$; Λ and Λ_p – accumulated and limited shear strain level at a given index of the stress state Π ; n – strain-hardening coefficient; φ_0 – coefficient, determined on the basis of the ductility tests. In non-reinforced metal $\Psi = 0$, and with a complete depletion of ductility resource $\Psi = 1$.

The plasticity curve is used as initial hardening characteristics $\sigma_s = \sigma_s(\Lambda)$, the curve of limited plasticity $\Lambda_p = \Lambda_p(\Pi)$ and the diagram of cyclic crack resistance $V=V(K)$ in the coordinates “stress intensity factor” K – fatigue crack growth rate V ”.

In the same terms and categories the solution of the problems of mechanics at the investigated stages is fulfilled and it is shown that technological inheritance manifests itself in the formation of hereditary loading programs depending on the geometric parameters of the deformation centers (DZs), acting as a set of initial and boundary conditions for solving the problems of deformation mechanics. The loading program was presented in the coordinates "stress state index Π – accumulative shear strain level Λ ".

The regularities of the metal plastic flow, the accumulation of deformation, the depletion of the metal plasticity reserve, the formation and transformation of the surface layer according to the studied loading stages are revealed, the rules of technological inheritance are formulated. The results of the

investigations made it possible to reveal in the processes of free orthogonal cutting, and in the SPD processes to confirm the presence in the deformation zone of three sections of quasimonotonic deformation, at the edges of which the deformation changes sign.

In particular, when processing by a SDP toroidal roller the force $P=2\ 500\ \text{N}$ it was found that most of the material in deformation zone is under compression, while the largest value of the average normal stress is observed in the zone of the tool contact with a part. The highest intensity values of shear stresses occur in the top zone of the wave front of a deforming tool. When moving deep into the surface layer absolute values decrease, but the distribution pattern of these components is practically unchanged. Such character of the loading scheme leads to the fact that the most intense accumulation of strain stress occurs in the front area of the deformation zone. As metal is reinforced, every subsequent operating cycle leads to a more "rigid" loading schemes, resulting in the accumulation of the limited deformations and complete depletion of metal ductility.

The results of fatigue tests of samples hardened by SPD showed that depletion of the plasticity reserve to a certain limit is useful from the point of view of increasing cyclic durability [13]. At the same time, this leads to the opposite effect at the stage of cyclic crack resistance, increasing the crack growth rate and shortening the duration of this stage. It has been established, that for each material and for each load program there is a certain level of depletion of the plasticity reserve, starting from which there is an increase in the intensity of the cracks growth rate.

Thus, the available range of variation, reached by SPD processing of the parameters of the mechanical state of the metal surface layer is limited both by the initial properties of the metal of the part and by the permissible range of changes in the technological parameters of the processing regime, which include the shape of the profile of the base circle roller.

At the same time, the expansion of the technological capabilities of SPD is possible due to the creation of processing schemes with large hydrostatic pressure and the number of sections of quasimonotonic deformation. This will lead to the accumulation of large deformations with relatively low exhaustion of the ductility reserve without destroying the surface layer of metal.

Results and discussions

The results of theoretical and experimental studies allowed to develop new designs of deforming tools, having complex working profile, that allows [15-17]:

- to vary widely the geometry of the working profiles, both in radial and axial direction;
- to create large interference of deforming elements in deformation zones;
- to create a complex stress state with predominantly large hydrostatic pressure;
- to obtain large deformations with a relatively low degree of exhaustion of the metal plasticity reserve.

The multiradius base circle roller (MR-roller) has the form of the working surface profile in the form of a combination of successively located deforming elements (DE) with radii of constant magnitude, disposed relative to each other with some displacement in the radial and axial directions [17].

Evaluation of the mechanical state of the deformation zone by the MP roller processing was carried out by the FE modeling method; the modeling material was assumed to be isotropic with mechanical parameters corresponding to the parameters of steel 45 (GOST 1050-88) in the state of delivery. A bilinear approximation of the flow curve was adopted, taking into account the hardening of metal. A flat-deformed setting was used; while the process of deformation accumulation and depletion of the plasticity reserve was simulated in the plane of feed that passes through the axis of rotation of the processed part [18].

As a processing surface a plane part of the main deformations of a cylindrical part with length $L = 70\ \text{mm}$ and height $h = 30\ \text{mm}$ was modeled (Fig. 1). As it is known, the plane of main deformations is located in the meridional section of the cylindrical work piece – the feed plane [7]. The lower and side boundaries of the work piece were rigidly fixed along both axes. The dimensions of the deformation zone appeared during the processing, are much less than the modeled fragment, so the edge effects, which occur in this situation, introduce a very insignificant error in the simulation results.

The indenter was modeled as an absolutely rigid body and was in the form of a circle modeling roller of a given profile radius. The surface material of the part, with the properties given in Table 1, was affected by a multiradius roller with profile radii: $R_{pr1} = 1\text{ mm}$ and interference $h_{d1} = 0.05\text{ mm}$; $R_{pr2} = 1\text{ mm}$ and interference $h_{d2} = 0.1\text{ mm}$; $R_{pr3} = 1\text{ mm}$ and interference $h_{d3} = 0.15\text{ mm}$; $R_{pr4} = 3\text{ mm}$ and interference $h_{d4} = 0.05\text{ mm}$.

In the plane of the main deformations, the displacement of the deformation zone in the direction of feed has discrete nature: a new DZ occurs with a displacement of previous one by the feed quantity.

In the initial position, the indenter was disposed to the surface with a certain gap. At the first and any subsequent odd step of modeling the loading was performed – the displacement of the indenter in the direction of the surface by a certain amount, assuming the introduction and creation of the interference specified for modeling. At the second and any subsequent even step of the simulation the unloading was performed – the withdrawal of the indenter from the surface to the initial distance with its simultaneous displacement along the surface by the feed quantity.

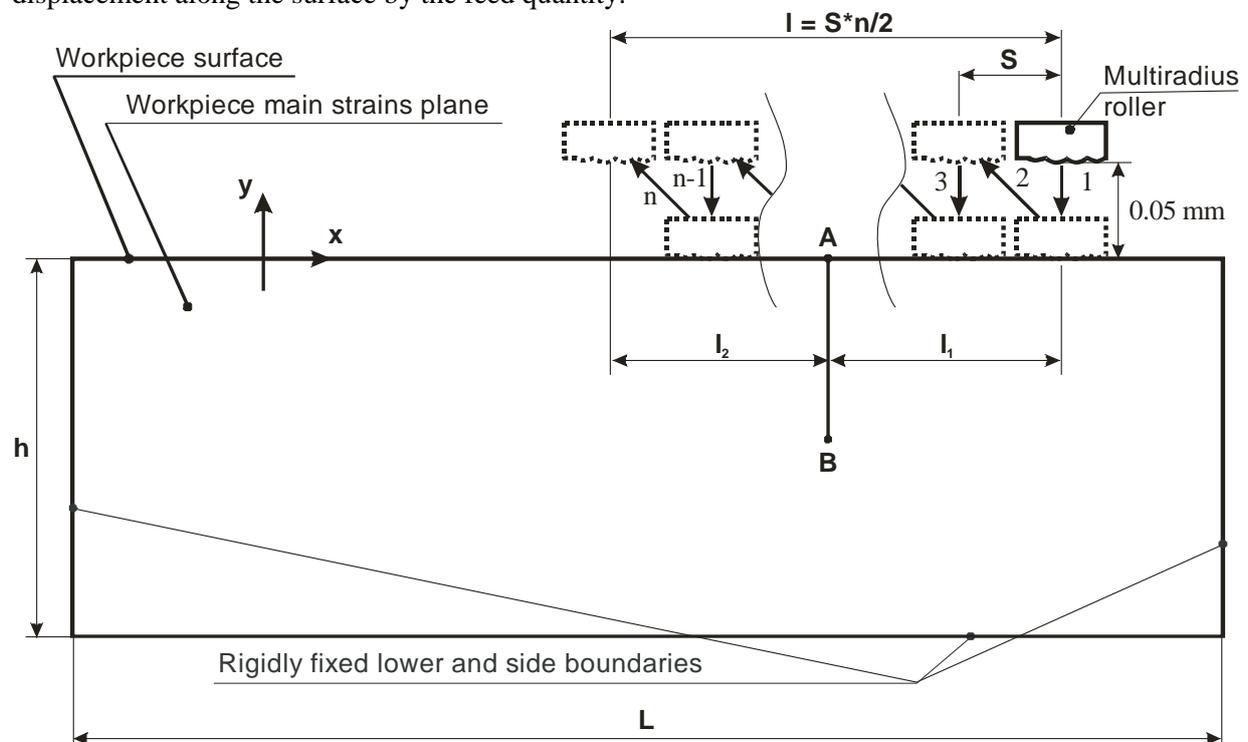


Fig. 1. Scheme for the formulation of the FEM modeling problem

In total, 340 steps were simulated – 170 loading steps and 170 unloading steps. The length of the processing surface in the presented model was $l = S \cdot n / 2 = 17\text{ mm}$.

Thus, in the process of realization of all simulation steps, this cross-section passes through the deformation zone space and is the very cross-section along the depth of the processing surface layer in which deformation accumulation took place, partial exhaustion of the plasticity reserve, and the formation of the residual stress tensor.

Table 1

Physical and mechanical properties of metal and parameters of the flow curve
(steel 45, GOST 1050-88, 160-180HV)

Young's modulus	E, MPa	2×10^{11}
Density	$\rho, \text{kg/m}^3$	7800

Poisson ratio	ν	0.3
Friction ratio	η	0.21
Extrapolated range of fluidity	σ_{ext}, MPa	3.66×10^8
Tangent modulus	T_{mod}, MPa	2.596×10^6

After solving the model in the selected section, the following values were fixed for each simulation step: the units' coordinates, the displacement components of the units, the stress tensor components, the tensor components of the elastic, plastic, and total elastic-plastic deformation.

For further calculations of the accumulated parameters of the mechanical state, the angle of deformation in the circumferential direction was assumed equal to 10^0 , the rotation frequency of the part being equal to 50 s^{-1} [7]. Thus, time of one rotation of the part was 0.2 s. For the assumed deformation angle in the circumferential direction, time of one cycle, during which the surface layer is loaded and unloaded, was 0.0054 s. At the same time, half of this time (0.0027 s) was spent on loading and the same time on unloading.

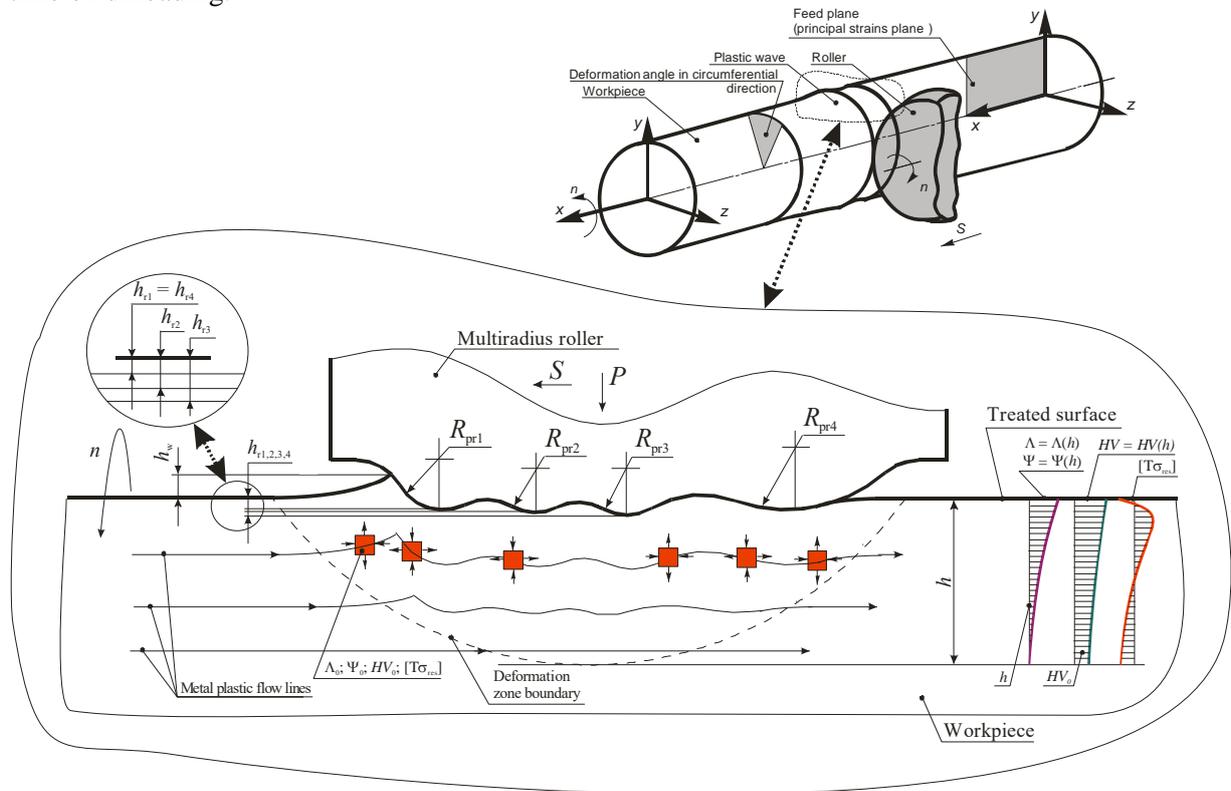


Fig. 2. The scheme of SPD processing by a multiradius roller

Subsequently, the components of the stress and strain tensors were recalculated into the coordinates of current flow line points in the deformation zone [19].

Figure 3 shows the profile of the deformation zone, reconstructed according to the results of FEM modeling. Figures 4-7 show the components distribution of the stress-strain state along the profile line of the deformation zone; while the abscissa points on the diagrams coincide with the abscissa of the profile.

The deforming element, which first comes in contact with the original (unprocessed) surface layer of the part, has a profile radius $R_{pr1} = 1 \text{ mm}$ and moves with interference $h_{d1} = 0.03 \text{ mm}$. As a result, the DZ arises that is identical in shape and size to the zone of deformation in the SPD processing toroidal roller.

The second deforming element also has a profile radius $R_{pr2} = 1 \text{ mm}$ and moves with interference $h_{d2} = 0.08 \text{ mm}$ relatively to the initial surface and interference of 0.05 mm with respect to the first deforming element. In this case, the zones of plastic flow are overlapped because of the action of the first and second deforming elements. Based on the ideas about the mechanics of SPD in the zone of this overlap, a change in the stress state scheme occurs, which leads to a change in the sign of plastic deformation.

The same effect is observed in all zones located between adjacent deforming elements.

The third deforming element with a profile radius $R_{pr3} = 1 \text{ mm}$ also moves with interference $h_{d3} = 0.13 \text{ mm}$ relative to the initial surface and interference of 0.05 mm towards the second deforming element.

The fourth deforming element with a profile radius $R_{pr4} = 3 \text{ mm}$ moves with interference $h_{d4} = 0.03 \text{ mm}$ relatively to the initial surface and interference of -0.1 mm towards the third deforming element.

Such construction of a multiradius roller leads to complex stress state of the metal, under which a repeated change in the sign of plastic deformation occurs.

Analysis of the results of FE modeling showed that the profile of the deformation zone with a confidence greater than 85% coincides with the experimental profile, obtained by the method of profilography after rapid removal / shooting of the MR roller from the surface of the work piece (Fig. 3). It indicates the formulation correctness of the FEM model and the solution of the problem of determining the components of the stress and strain tensors.

The second important conclusion is that metal is under compression in the upper deformation zones (Figure 4).

The components of the stress tensor change in accordance with the profile of the deforming elements of the MR roller. The component σ_x in the zone of the front non-contact surface before the first deforming element is firstly reduced to the level of -380 MPa, then increases to -230 MPa in the top zone of the plastic wave. The component σ_y decreases to the level of -850 MPa, and the σ_{xy} component first increases to +75 MPa, then decreases to -85 MPa in the top zone of the plastic wave. In the zone of the front contact surface of the first deforming element, growth occurs firstly, the numerical value of the component σ_x decreases to -630 MPa, then again grows to -550 MPa at the top point of the profile of the first deforming element. In the same zone, the component σ_y continuously increases to a value of -190 MPa, and the σ_{xy} component reaches positive values of +175 MPa.

In the transition zone between the first and second deforming elements at points with abscissas equal to 4.2-5.2 mm, the component σ_x increases, the component σ_y decreases to -1300 MPa, and the σ_{xy} component first decreases to -180 MPa, then grows.

In the front contact zone of the second deforming element, the σ_x component decreases sharply to -980 MPa, the component σ_y begins to increase, and the σ_{xy} component increases to +200 MPa.

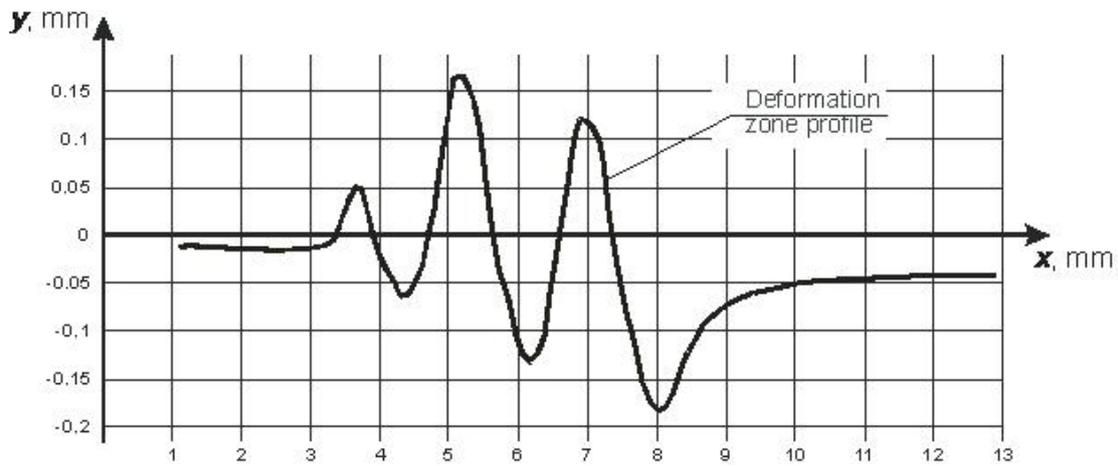


Fig. 3. Profile of deformation zone reconstructed from the results of FEM modeling

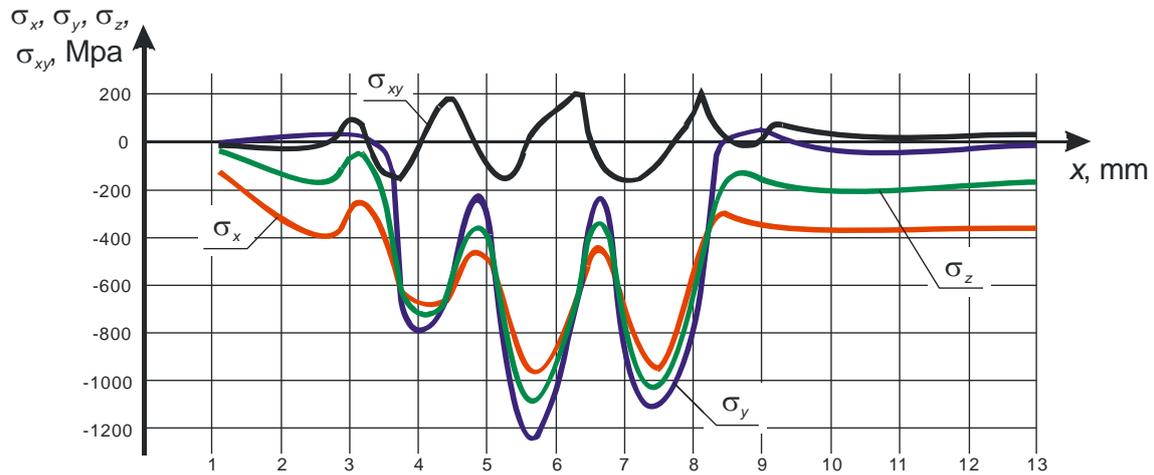


Fig. 4. Distribution of stress tensor components

In the transition zone between the second and the third deforming elements, as well as in the contact zone of the third deforming element, there is the same example of changes in the components of the stressed state.

In the transition zone between the third and the fourth deforming elements, the components σ_x and σ_y grow, but the σ_{xy} component decreases.

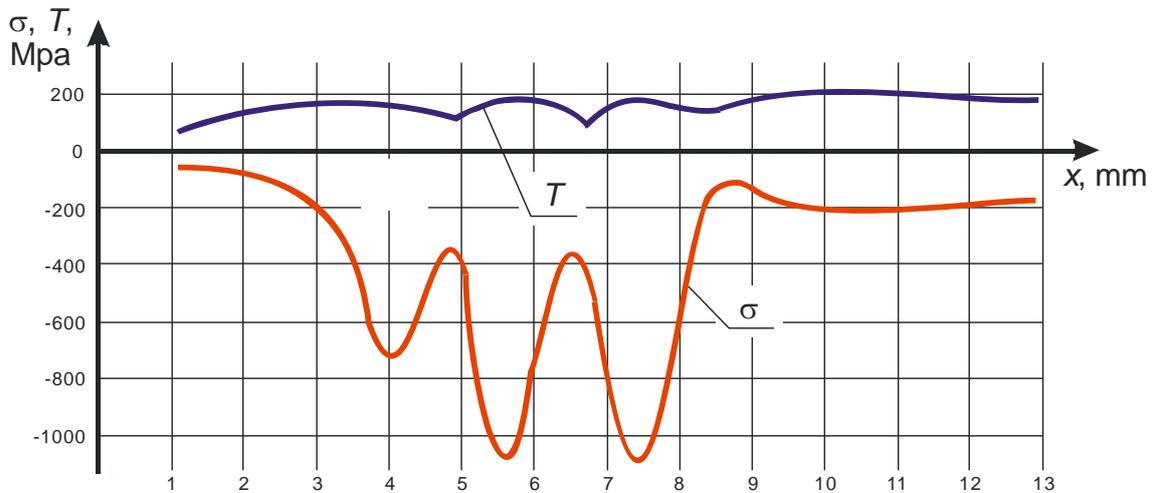


Fig. 5. Distribution of average normal stress and shear stresses intensity

The average normal stress repeats the tendencies of the changes in the components of the stressed state and shows that the deformation zone is under compression (Fig. 5). In this case, under the second and the third deforming elements, special conditions are attained at which maximum hydrostatic pressure reaches 1150 MPa.

The third important conclusion is that, in difficult situation of metal flow in the same characteristic zones, the values and sign are changed repeatedly according to the same tendencies of deformation rates (Fig. 6).

Thus, the accumulation of the deformation degree of the shear and the depletion of metal ductility reserve occurs continuously with the index negative value of the stress state diagram (Figure 7). Moreover, even with a significant accumulated deformation of $\Lambda \approx 7$ due to a favorable deformation scheme, the degree of depletion of ductility reserve does not exceed $\Psi \leq 0.62$.

The results of the research showed that when a traditional construction is processed by a toroidal roller:

- the accumulation of the limiting deformation $\Lambda \approx 1.24$ would lead to the limited metal state $\Psi = 1$ at the profile radius $R_{pr} = 1 \text{ mm}$ and interference $h_d = 0.03 \text{ mm}$;
- the accumulation of the limiting deformation $\Lambda \approx 1.24$ would lead to the limited metal state $\Psi = 1$ for a profile radius $R_{pr} = 3 \text{ mm}$ and interference $h_d = 0.05 \text{ mm}$;
- the interference $h_d = 0.15 \text{ mm}$ at the profile radius $R_{pr} = 1 \text{ mm}$ is not permissible, because when the tool is inserted for several rotations of the part results to a nonpermanent deformation zone. This is the catastrophic growth of the plastic wave ahead of the deforming tool and the destruction in its top zone;
- SPD processing with the specified strains and profile radii successively by second, third and fourth operating cycle leads to accumulation of limited deformations and complete exhaustion of metal plasticity reserve after the first operating cycle.

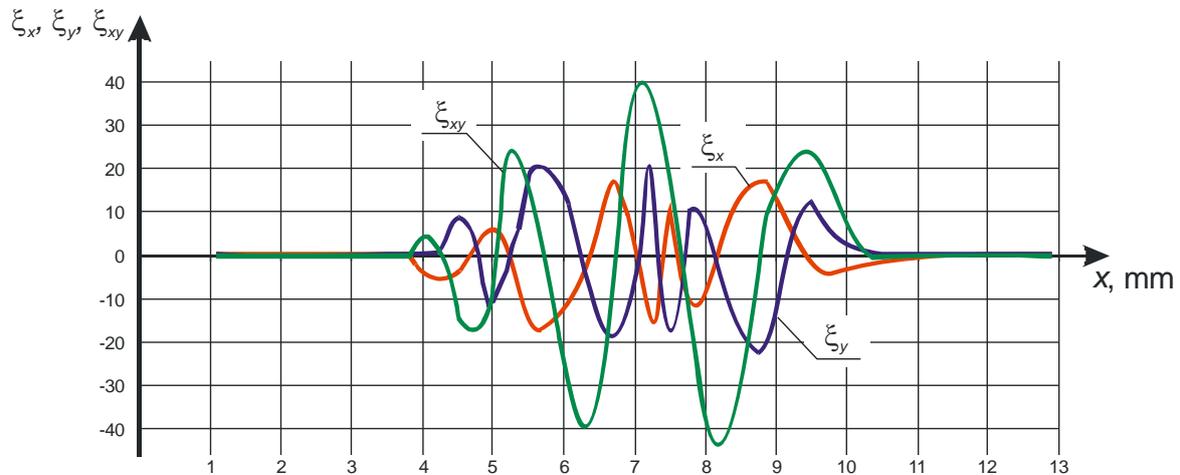


Fig. 6. Distribution of the tensor components of the strain rate

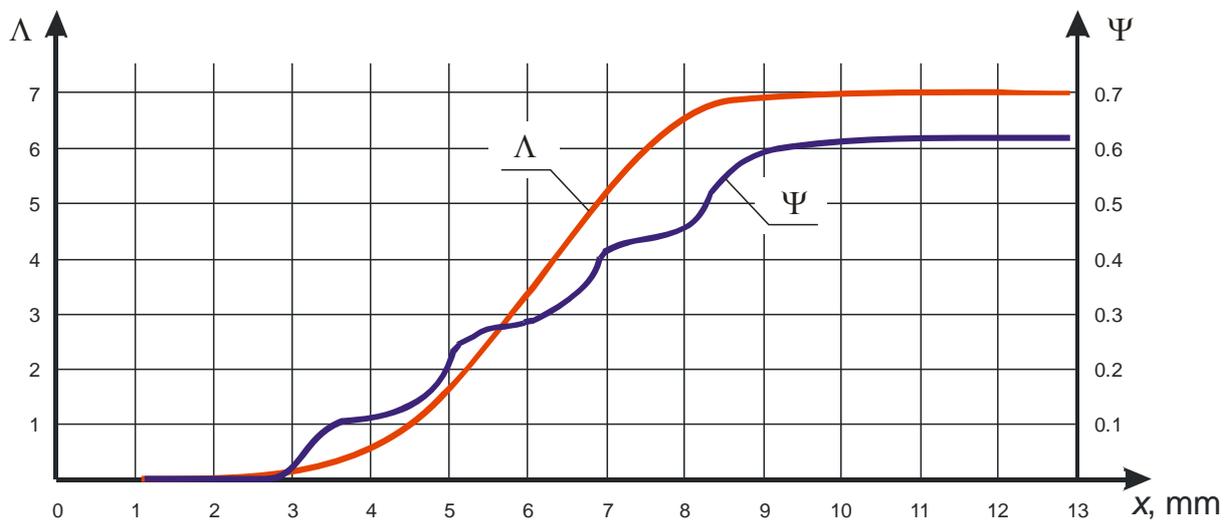


Fig. 7. Accumulation of shear deformation degree and change in the depletion degree of metal plasticity reserve

The conducted researches showed that the considered profile design of the working piece of the roller allows to accumulate large deformation values without destroying the metal of the surface layer, which provides additional possibilities for assurance both cyclic durability and cyclic crack resistance.

Metal micro-hardness investigations of the deformation zone and the surface layer hardening, carried out on the device mod. DuraScan 20, confirmed the received laws.

Conclusions

1. Schemes and methods improvement, development of new tools and technologies is based, first of all, on modeling of machining processing. Modern finite-element software products allow to develop high-quality models, as their comparison with experimental tests testify. At the same time, the quality of calculations is determined by the quality of the physical model, based on modern ideas about the mechanics of a deformed solid body.

2. Knowing physical regularities of the metal plastic flow, calculation of the stress-strain state and evaluation of the accumulated deformations and plasticity in the process and after the processing has

allowed to develop a number of unique methods and processes that ensure high quality of the surface layer and, accordingly, high durability of the processed machines parts.

3. The efficiency (intensification) increase of the processes of "cold" mechanical hardening processing, is possible by creating complex stress-strain state with predominant schemes with high hydrostatic pressure in the deformation zone. In turn, such schemes are implemented by tools that have complex geometry and provide a certain kinematics of metal flow.

4. The results of the theoretical and experimental studies have allowed to develop new designs of deforming tools having the complex working profile. The proposed designs make it possible to create large tension and complex stress state in the deformation zone with predominantly large hydrostatic pressure, which leads to the accumulation of large deformations at relatively low degree of metal plasticity reserve depletion.

5. There was the FE-modeling by SPD processing with a multiradius roller, which has the form of a working surface profile in the form of a combination of successively located deforming elements with radii of constant magnitude, located relative to each other with some displacement in the radial and axial directions. The situation of the metal plastic flow in the deformation zone under the conditions of a complex stressed state is revealed and is shown that the considered profile of the working part of the roller allows to accumulate large values of strains without destroying the metal of the surface layer. In turn, this provides additional opportunities to ensure both cyclic durability and cyclic crack resistance of products.

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