# MECHANICS OF TECHNOLOGICAL INHERITANCE

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**Abstract:** *Increasing demands for the quality and longer service life of machine parts require methods of strengthening treatment with plastic deformation of the surface (PDS). The PDS processes become significantly more efficient when technological inheritance is taken into consideration. The mechanics of technological inheritance was developed by the author and exemplified by the life cycle of a part, including processes of cutting and PDS as well as fatiguing, which occurs during the operation stage. Theoretical and experimental findings include key patterns of technological inheritance and can be applied to engineering of efficient strengthening processes.*

**Keywords**: TECHNOLOGICAL INHERITANCE, DEFORMATION SITE, DEGREE OF SHEAR DEFORMATION, PLASTICITY RESERVE

## *1. Introduction*

One of the crucial challenges of contemporary machine engineering is to make sure using processing methods that machine parts have a longer service life. The service life of machine parts is, in many ways, determined by the behavior of the surface layer. Its parameters are formed throughout the entire design process. Among the processing methods which improve the service life of a part at final stages of the processing route are the methods of plastic deformation of the surface (PDS) that are widely applied to manufacture. Practical application has proven that with the correctly assigned modes of PDS the service life of a part can increase 5 times or more. At the same time, the incorrectly assigned PDS modes and disregard of properties accumulation occurring prior to PDS can cause the rupture of the surface during the manufacture or premature failure of the part during operation.

When designing a route for strengthening machining and when evaluating the service life of a machine part technological inheritance (TI) has to be taken into account. This means exposing and applying the functional dependencies between the parameters of the surface behavior and performance parameters. That, in its turn, requires an analysis of that behavior initiation at all stages of the life cycle of a part. In most cases, the dependency between the surface layer and technology, on the one hand, and the surface layer and the part service life, on the other hand, is established empirically. That, in its turn, contradicts to the practical application needs because new materials, new articles and new operation conditions require a whole new set of time-consuming and labor-intensive experiments.

The author underlines four crucial aspects.

1. Manufacturing engineering is developed to the point when the accumulation of scientific facts and findings do not generate new knowledge any more.
2. High rates of machine engineering development, occurrence of new materials and more complicated machine operation environment require a shorter period for design-to-manufacture facility by reducing experiments and increasing design work. That, in its turn, generates the necessity in more complex but also more accurate models of metal behavior under loading. It is especially critical for strengthening treatment.
3. A plethora of specific data, unfortunately, can not always make the basis for contemporary automated process engineering techniques. That requires the exposure and description of physical dependencies between the phenomena and processes under study. It also requires making the information obtained systematic and structured to be further used in contemporary information technologies.
4. The patterns of technological inheritance are too complex to be exposed as various stages of surface stressing (e.g., cutting, plastic deformation of the surface, operation fatiguing) are currently studied by means of various methodologies and definitions.

Despite the complexity of the phenomena that develop in the surface layer, the author has described them from a phenomenological perspective using the fundamentals of the mechanics of deformable environments. The core of this approach is that the physical behavior of the surface layer is interpreted as a result of the plastic flow of metal within the deformation site, with the plastic flow developing under the conditions of complex stress-strain behavior. This approach includes not only the conventional parameters of surface layer behavior such as roughness, waviness, hardness, residual stresses but also the degree of shear deformation, degree of plasticity reserve depletion, which are well-known in strain theory.

The life cycle of a part is seen as a continuous process of depletion by the metal surface layer of plasticity reserve. The stages and steps of such process are controlled by stressing programs.

The models of formation and transformation of the surface layer during cutting, plastic deformation of the surface (PDS) and operation fatiguing were developed and patterns of such phenomenon were studied. The end-to-end analysis and computations of hereditable deformation parameters of the surface layer during machining and operation of parts were carried out.

In addition to the above, the processes occurring in the surface layer were described in a way adapted to the use by engineers.

## *1. Problem solution: prerequisites and aids*

Technological inheritance is one of the key areas of research study in machine engineering, which has been done in the Soviet Union and Russia since 1930s.

When analyzing how accurate metalcutters can process machine parts, Sokolovsky A.P. found that inaccuracies copy themselves throughout the entire design process [1]. Kovan V.M. suggested a dimensional analysis from the final (assembly) to the initial (workpiece) manufacturing stages [2]. At that time the part to be manufactured carried hereditary information and its accuracy characteristics were getting “copied” (inherited) throughout the entire design process.

By early 1960s demands for reliability of machine parts increased and that, in its turn, required a new approach to evaluating engineering procedure. After performing a set of studies researching the accuracy and quality of the surface of parts of bearings Yatsheritzyn P.I. established that the properties of treated surfaces had to be studied in relation to the whole set of performed operations [3]. Together with Ryzhov E.V. and Averchenkov V.I. he showed that a design process includes certain “barriers” that disrupt some parameters describing the surface layer of a product [4]. There are positive and negative factors of technological inheritance. During process engineering the structure of a process should involve operations, which would generate more obstacles for negative factors to reach the final operation.

A.M. Dal’skiy proved that inheritance played a role in making sure that high-precision parts of machines are reliable [5]. Together with A.S. Vasilyev and A.I. Kondakov, he gained new knowledge about process environments [6]. Primary forms of inheritance were established such as parametric and structural and, also, the inheritance of interaction characteristics between a workpiece and its external environment, which are found in process environments at various levels. The prevalent opinion is that hereditary information is carried by the thin surface layer, which is getting formed throughout the entire design process.

A.G. Suslov believes that technological inheritance is represented by various structural models [7].

The author of this article developed the scientific foundation for the mechanics of technological inheritance. Its fundamentals are shown below [8].

1. The conceptual foundation of technological inheritance is formed by the fundamentals of the strain and fracture mechanics.
2. The TI mechanics is based on the categories of life cycle (LC) and continuous processes of deformation accumulation and depletion of plasticity reserve in the metal surface layer of a part during machining and operation that follows.
3. The fundamentals of TI mechanics are exemplified by the life cycle of a part, including cutting, plastic deformation of the surface and operation fatiguing affected by cyclic loading.
4. Each machining or operation step is seen as a stressing stage. Stressing stages are interpreted through stressing programs and how complete they are. They are described in terms of the phenomenology of deformation accumulation and plasticity reserve depletion.
5. Stressing stages are divided into a set of steps of quasimonotonous deformation, which determine the patterns of deformation accumulation in the surface layer of a part.
6. Operation fatiguing, in its turn, involves two stages. The first one begins with cyclic loading and ends with the point of the complete depletion of plasticity reserve and the occurrence of visible faults (cyclic life stage). The second stage begins with the point of surface material discontinuity and ends with the complete failure of a part (separation into fragments) and is described with the cyclic crack growth diagram (cyclic crack growth stage).
7. Interrelated deformation processes occur in the surface at each stressing stage and step. According to the ideas of mechanics, during stressing at each stage there occurs a deformation site (DS), plastic deformations accumulate, plasticity reserve of metal is gradually depleted, residual stresses occur and transform. Thus, the surface layer is getting formed with specific hereditable properties.
8. Ontological models of processes are based on the patterns of formation and transformation of the deformation site at the stages of life cycle.
9. At each stage the deformation site forms under the exposure to stressing. The behavior of the DS reflects the surface behavior. The DS is the carrier of hereditary information; its form, dimensions and behavior are fully and adequately determined by the properties accumulated (inherited) prior to that.
10. TI is seen as a common pattern when deformation accumulation at a certain quasimonotonous stage is determined by stressing program and its history. The evaluation of stressing programs is made on the basis of the computation of DS stress and strain state (SSS).
11. Stressing history is described in terms of stressing programs within the prior time periods. Stressing history affects the stressing programs at a certain stage by altering the intensity of deformation accumulation and plasticity reserve depletion.
12. TI is exemplified by the terms of non-hereditable (reversible) and hereditable (irreversible) damage or by the terms of depleted and residual plasticity reserve.
13. The TI mechanics governs engineering techniques of new design of strengthening treatment by means of PDS, of plasticity control and of efficient control for the surface behavior at each stage of stressing by means of physical methods.

## *3. Solution to the problem under discussion*

We are discussing the life cycle of a machine part undergoing the stages of cutting, plastic deformation of the surface and stressing with the exposure to operation cyclic loading. A more characteristic type of fatiguing is multicycle stressing of a machine part, which, in its turn, includes two stages such as cyclic life and fatigue crack growth.

Parameters known as terms of mechanics of deformable solids are used for TI mechanics problem solving:

- Stress state index:

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

- Degree of shear deformation:

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

- Residual stress tensor:

$$[\mathrm{T}\sigma_{\text{ост}}]_{ij} = \left[\mathrm{T}\sigma_{\text{деф}}\right]_{ij} + \left[\mathrm{T}\sigma_{\text{раз}}\right]_{ij} + [\mathrm{T}\sigma_t]_{ij}; \tag{3}$$

- Degree of plasticity reserve depletion [9]:

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

where $\sigma$ – average normal stress; T – shear stress intensity; $\sigma_1, \sigma_{2,} \sigma_3$ – principal components of a stress tensor; $\xi_x, \xi_y, \xi_z, \eta_{xy}, \eta_{yz}, \eta_{zx}$ – components of a deformation rate tensor; $\left[\mathrm{T}\sigma_{\text{деф}}\right]_{ij}$ – load stress tensor; $\left[\mathrm{T}\sigma_{\text{раз}}\right]_{ij}$ – unloading stress tensor; $[\mathrm{T}\sigma_t]_{ij}$ – thermal stress tensor; $\Psi_1$– component dependent on flow stress or on accumulated deformation; $\Psi_2$ – component dependent on metal plasticity with $\Pi = const$; $\Lambda$ and $\Lambda_p$ – accumulated and maximum permissible degree of shear deformation with a certain stress state index $\Pi$; $n$ – strain-hardening coefficient; $\varphi_0$ – coefficient determined by plasticity tests. In unstrengthened metal $\Psi = 0$, when plasticity reserve is completely depleted, $\Psi = 1$.

The TI mechanics is based on continuous deformation accumulation and plasticity reserve depletion in the surface of a part affected by stressing programs.

Strengthening curve $\sigma_s = \sigma_s(\Lambda)$, ultimate plasticity curve $\Lambda_p = \Lambda_p(\Pi)$ and fatigue crack growth diagram $V = V(K)$ in the coordinates «stress intensity coefficient $K$– fatigue crack growth rate $V$» are used as initial metal characteristics.

It is assumed that the surface behavior is known and is described in terms of deformation mechanics for the case of annealed work material as

$$\begin{cases} \Lambda_{ij|i=0,j=0} = 0; \\ \Psi_{ij|i=0,j=0} = 0; \\ \Lambda_p = \Lambda_p(\Pi); \\ [\mathrm{T}\sigma_{\text{ост}}]_{ij|i=0,j=0} = 0, \end{cases} \tag{5}$$

where $i$ stands for the number of a stressing stage and $j$ – for the number of a quasimonotonous step at this stage.

It is established that machining by cutting and by plastic deformation of the surface comprises three steps of quasimonotonous deformation. Deformation alternates where these steps approach each other and plasticity reserve partially recovers.

The first stage – cutting – starts with initial (zero) values of deformation and of degree of plasticity reserve depletion (fig. 1).

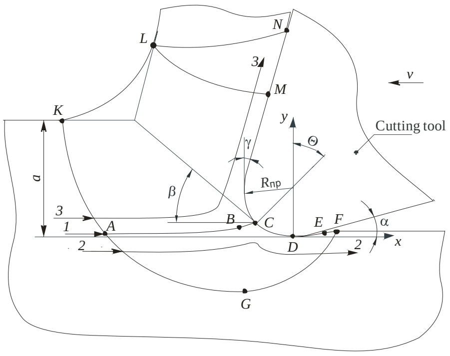

***Fig. 1.*** *Orthogonal cutting model:*
*$\alpha$ – rear angle; $\gamma$ – front angle; $\rho$ – tool edge radius; $\Theta$ – indentation angle; $a$ – cutting depth; $S$ – feed*

According to the flow pattern, deformation site *KLMCDEFGAK* is seen to comprise two areas: higher and lower than some current line 1, which overlaps with line *ABC*.

The deformation site contour during cutting is described with a set of points and lines: $KL$ – non-contact swarf edge; $LM$ – end line of metal plastic flow; point $M$ stands for the end of plastic contact of swarf with the cutting tool and point $N$ – point of separation of swarf from the cutting tool front surface, it stands for the end of elastic contact of swarf with the cutting tool; $KAG$ – starting line of metal plastic flow (front boundary of deformation site); point $G$ stands for inmost depth of plastic deformation growth; $GF$ – end line of metal flow (back boundary of deformation site); $ABC$ – critical current line, which separates metal flows into those turning into swarf and those going under the tool; $MCDE$ – cutting tool contour line; $EF$ – back non-contact edge; point $E$ – point of separation of the cutting tool from the treated surface.

The metal plastic flow occurs along current lines with some of them (e.g. current line 3-3) being displaced into swarf and the others (e.g. current line 2-2) being displaced under the tool. Some critical current line 1 ($ABC$) is the boundary between them.

Deformation accumulates and plasticity reserve is depleted along current lines under the conditions of a certain state of stress with the swarf creating additional hydrostatic stress and altering the nature of SSS in the area of *ABCDEFG*.

Depending on the stressing diagram and degree of plasticity reserve depletion metal flows may split at point *A*, along current line *ABC* (1-1) or at point *C*, which will generate miscellaneous kinds of swarf.

Within the three stages of quasimonotonous deformation: deformation $\Lambda_{\text{рез}}$ accumulates, plasticity reserve is partially depleted by the value of $\Psi_{\text{рез}}$, residual stresses described by tensor $[\text{T}\sigma_{\text{ост}}]_{\text{рез}}$occur in the surface:

$$(6)\quad\begin{cases} \Lambda_{\text{рез}} = \Lambda_{ij|i=1,j=3} = \sum_{j=1}^{j=3} \Lambda_j\,; \\ \Lambda_p = \Lambda_p(\Pi); \\ \Psi_{\text{рез}} = \Psi_{ij|i=1,j=3}; \\ \Psi_{\text{рез}} = \int_0^{\Lambda_{\text{рез}}} \left[ n\varphi_0\Lambda_j^{n-1} + \left(1-\varphi_0\Lambda_p^n\right)\frac{1}{\Lambda_p} \right] d\Lambda; \\ [\text{T}\sigma_{\text{ост}}]_{\text{рез}} = [\text{T}\sigma_{\text{ост}}]_{ij|i=1,j=3}. \end{cases}$$

The surface behavior after the treatment by cutting is initial for the stage of PDS (fig. 2).

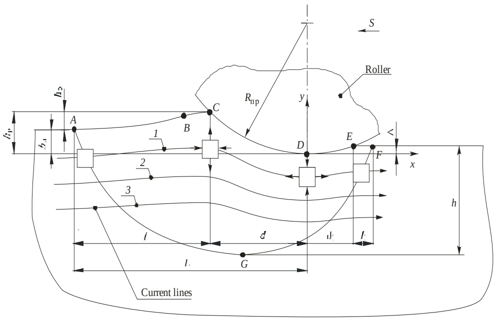

***Fig. 2.*** *PDS model: $S$ – feed; $R_{\text{пр}}$ – contour radius of deforming tool (roller)*

The PDS process is viewed in the axial section of the shaft where the plane of principal deformations is located. The following points, lines and areas were specified in the DS cross-section: $h_{\text{д}}$ – active preload, equal to the depth of the tool indentation; $h_{\text{в}}$ – height of elastic and plastic wave prior to the deforming tool; $h_{\text{р}} = h_{\text{д}} + h_{\text{в}}$– estimated preload, equal to the elevation view of the contact front arch; $\Delta$ – height of elastic and plastic metal recovery following the deforming tool; $\Delta d$– length of the bottom view of the contact front arch (length of the DS contact front zone); $d_1$ – length of the bottom view of the contact rear arch $DE$ (length of the DS contact rear zone); $l$ – wave length preceding the deforming tool (length of the DS front non-contact area); $L = l + d$ – length of the DS front area; $l_1$– length of the DS secondary area. Along the DS cross-section plastic deformation occurs at point $A$ and ends at point $F$. The DS cross-section includes front non-contact area $ABC$, contact area $CDE$ and rear non-contact area $EF$. The front non-contact area, in its turn, comprises concave line $AB$ and convex line $BC$.

When the surface layer is exposed to stressing, material particles move into the DS along current lines 1, 2 and 3, plastic deformation reaches depth $h$. It results into the surface layer characterized with a various depth for shear deformation, plasticity reserve utilization and residual stress tensor.

Close enough interrelation exists between the DS geometric parameters. Moreover, close interrelation is found between the DS parameters, on the one hand, and segments of treatment modes and surface quality parameters, on the other [8].

The interrelation specified above is used to describe boundary and initial conditions for TI mechanics problem solution.

Residual stresses as a result of cutting are removed during the PDS stage, involving stressing and creation of plastic deformation site. Within the three steps of quasimonotonous deformation: plastic deformation keeps accumulating and plasticity reserve keeps getting depleted. It results in a new behavior of the surface characterized by a specific degree of shear deformation, of plasticity reserve depletion and residual stress tensor:

$$(7)\quad\begin{cases} \Lambda_{ij|i=2,j=0} = \Lambda_{\text{рез}}; \\ \Psi_{ij|i=2,j=0} = \Psi_{\text{рез}}; \\ \Lambda_{ij|i=2,j=3} = \sum_{j=1}^{j=3} \Lambda_j = \Lambda_{\text{ППД}}; \\ \Lambda_p = \Lambda_p(\Pi); \\ \Psi_{\text{ППД}} = \Psi_{ij|i=2,j=3} = \\ = \int_{\Lambda_{\text{рез}}}^{\Lambda_{\text{ППД}}} \left[ n\varphi_0\Lambda_j^{n-1} + \left(1-\varphi_0\Lambda_p^n\right)\frac{1}{\Lambda_p} \right] d\Lambda; \\ \Lambda_{\text{мех}} = \Lambda_{\text{рез}} + \Lambda_{\text{ППД}}; \\ \Psi_{\text{мех}} = \Psi_{\text{рез}} + \Psi_{\text{ППД}}; \\ [\text{T}\sigma_{\text{ост}}]_{ij|i=2,j=0} = [\text{T}\sigma_{\text{ост}}]_{\text{рез}}; \\ [\text{T}\sigma_{\text{ост}}]_{ij|i=2,j=1} = 0; \\ [\text{T}\sigma_{\text{ост}}]_{ij|i=2,j=3} = [\text{T}\sigma_{\text{ост}}]_{\text{ППД}}. \end{cases}$$

Value $\Psi_{\text{ППД}}$ stands for a degree of plasticity reserve depletion during PDS, involving the stressing history. Within two machining stages such as cutting and PDS degree of shear deformation $\Lambda_{\text{мех}}$

has been accumulated and plasticity reserve $\Psi_{\text{мех}}$ has been depleted. In addition, the residual stress tensor depends on the total accumulated deformation.

The mechanics models for multicycle fatiguing such as cyclic life and fatigue crack growth during operation were introduced.

The initial state for cyclic life is described with values $\Lambda_{\text{мех}}$, $\Psi_{\text{мех}}$ and $[\mathrm{T}\sigma_{\text{ост}}]_{\text{ППД}}$. This stage is characterized by further accumulation of deformation occurring when tensors of operation (fatigue) $[\mathrm{T}\sigma_{\text{уст}}]$ and residual $[\mathrm{T}\sigma_{\text{ост}}]_{\text{ППД}}$ stresses go in with each other. Compressive residual stresses after the exposure to PDS result in more favorable fatiguing diagrams.

In each fatiguing cycle the degree of shear deformation continues to accumulate and plasticity reserve continues to deplete itself where there is quasimonotonous deformation. Residual stresses partially get partial relaxation. At the completion moment of cyclic life the residual stress tensor equals to 0.

During cyclic life, deformation $\Lambda_{\text{ЦД}}$ has accumulated and plasticity reserve $\Psi_{\text{ЦД}}$ has been depleted. As a result, within the three stages of cutting, of PDS and of cyclic stressing ultimate deformation has accumulated and plasticity reserve has completely been depleted at a point of probable surface metal failure. That behavior is denoted by value $\Psi = 1$; there appears a visible crack in the surface.

Further fatiguing (stage of fatigue crack growth) is described in terms of fatigue crack growth diagrams $V = V(K)$ in the coordinates «stress intensity coefficient $K$– fatigue crack growth rate $V$». The crack development begins with threshold coefficient of stress intensity $K_{th}$ and ends with the ductile failure of a part specimen corresponding to critical coefficient of stress intensity $K_{fc}$.

Fatiguing ends with a complete fragmentation of a part, which is described by the parameters of failure damping.

At various stages and steps of the life cycle of a strengthened part any exposure can be applied to an extent that will increase their duration. First of all, we are speaking of thermal exposure that will enable complete or partial recovery of initial properties (metal plasticity reserve). This can be a mechanical action altering the character of load application and generating a new mechanical state of a product and so on. The structure of process model and kinetic equations incorporates other thermal and mechanical stressing stages.

## 4. Findings and discussion

Theoretical and experimental study of the mechanics of technological inheritance was performed. It is found that the surface properties formation is affected by stressing programs $\Lambda = \Lambda(\Pi)$, which are shown in the coordinates «stress state index $\Pi$ – degree of shear deformation $\Lambda$».

The stressing program-based TI patterns, which have been specified, are shown below.

1. Technological inheritance exposes itself in the formation of hereditary stressing programs in relation to hereditary deformation sites, which act as a set of initial and boundary conditions for problem solution occurring in the strain mechanics.
2. Stressing history is described in terms of the programs occurring at the prior stressing stages.
3. At each following stage technological inheritance manifests itself through the transformation of stressing programs compared to the stressing programs of the material lacking such strain history.
4. Inherited stressing program «fades out» and deformation accumulation rate reduces at each following stage subject to the exponential hereditary law.
5. Residual stress state in terms of inheritance depends on total (accumulated) values of deformation degree and degree of plasticity reserve depletion.
6. Residual stress state together with the stresses caused by external loading forms an index and, thus, forms a stressing program at the stage of cyclic life.
7. Technological inheritance is a pattern. It is a characteristic feature of prior stressing programs to affect the formation of stressing programs at the following stages, which are also the results of specific stressing history of the metal surface of a product.

## 5. Conclusion

The description of technological inheritance is, first of all, the description of the impact of the complex alternate character of plastic deformation flow within the prior time periods on the formation of properties during the stressing stage under study.

Solving problems by means of terms and concepts of the mechanics of strain does not mean denying conventional beliefs about the surface quality of machine parts. At the same time, it means that in order to study technological inheritance more completely and profoundly, primary (ontological) patterns of surface formation, which have been accumulated throughout science advancement, can be applied as boundary and initial conditions to the solution of problems arising in mechanics.

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