Regularities of technological inheritance in the categories of loading programs

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Abstract. The paper presents an approach to describing technological inheritance as a pattern of changing loading programs under the influence of the loading history of the metal of the surface layer at the previous stages of processing. The loading program represents the regularity of the accumulation of deformation under conditions of a change in the stress state in the process of deformation and determines the regularities of the accumulation of metal damage during the processing and operation of the product. The proposed approach makes it possible to assess the accumulation of deformation and damage to the metal of the surface layer at all stages of the product life cycle.

1. Introduction
The increasing requirements for the durability of machine parts, including those operating under conditions of application of cyclic loads, require continuous improvement of methods and technologies, including hardening processing. In this case, the parameters of the quality of the surface layer after machining are important, including the parameters of the microstructure, roughness, hardening, residual stresses, etc. Ensuring the optimal ratio of these parameters requires the development of a methodology for predicting their formation at the processing stages and manifestation at the operation stage. This is possible based on taking into account subtle physical phenomena and evaluating the plastic flow of the surface layer material when exposed to cutting or deforming tools. In this case, it is important to transfer properties from previous operations to subsequent ones, i.e. accounting for technological inheritance (TI). This research area has been developed quite intensively over the past 50 years [1-3].

Further research and considering of TI made it possible to analyze various designs, technologies and manufactures of products from various materials at various stages of the life cycle. Therefore, the authors [4] investigated the surface quality and fatigue strength of structural titanium alloys. The regularities of the technological inheritance of such material properties as strain hardening, residual stresses, fatigue strength, etc. were established. The results made it possible to determine a process that is beneficial from the standpoint of fatigue strength and efficiency. In the work [5] it is shown that the physical integration of reproductive information, as well as sensory abilities in relation to the loads on the components during their life cycle should be implemented in the component itself. Technological inheritance was taken into account in the study of technological processes for the production of metal products in the form of a sequence of macroscopic, microscopic and submicroscopic transformations, typical for the initiated structure [6].

The method of nanostructuring deformation was used, which allowed the authors to formulate the foundations of a strategy for evaluating various multi-stage materials developing processes to achieve the required set of properties. Technological heredity in the form of a multilevel hierarchical system is used to describe the production of products from polymer composite materials (PCM) [7]. In this case,
products can be represented using graph theory, a distinctive feature of which is the implicit representation of the input-and-output relationship. The technological interrelationships of all individual transitions and operations are identified, which can contribute to either an increase or decrease in the performance characteristics of products.

The authors [8-9] propose to use the paradigm of technological inheritance to control production and use of components, analyze and use the collected data in the development of the next generation of a component, and to obtain an optimized structure. This approach allows you to create new generations of products based on the life cycle data of previous generations, which are more adapted to the new requirements of the actual environment. A.G. Korchnunov [10] proposes a formalized concept of technological heredity in relation to quality control in equipment manufacturing processes; at the same time, TI is described using fuzzy models based on the theory of fuzzy sets. The article [11] is devoted to the influence of TI stress-strain state on the accuracy and dimensional stability of non-rigid parts such as shafts, which made it possible to determine the negative inherited factors and improve the process of manufacturing non-rigid shafts. A.N. Ovseenko performed an analysis of the quality of the surface layer of parts of low rigidity, taking into account the influence of TI [12]. The revealed regularities of TI made it possible to form the quality of the surface layer of parts, optimal from the point of view of fatigue life, at the stage of its technological design by performing a rational sequence of finishing and hardening, and thermal operations [13]. Some authors [14] believe that it is expedient to describe TI of the operational properties in the processes of manufacturing parts by a graph reflecting the transmission coefficients and the mutual influence of physical-and-mechanical and geometric parameters. The research made it possible to develop methods of technological management and control of the inheritance of the operational properties of parts, including measurements of the physical, mechanical and geometric parameters of the material and surface for the most critical parts. The work [15] shows the rational influence of TI in the processes of manufacturing and restoration of the rods and journals of the crankshaft. Based on the research results, it was recommended to monitor and control the plasma metallization operation to ensure stable hardness and thickness of the coating; to regulate the depth of cut and the feed of the grinding wheel with a uniform allowance at the final machining operations. The TI analysis during the restoration of the working surfaces of the crankshafts and camshafts of the engines made it possible to revise the sequence of technological transitions and regulate technological influences [16]. In [17], it was shown that the purposeful formation of the surface layer, taking into account TI, is one of the most important tasks of the technological process of manufacturing parts with nano- and submicro crystalline structure.

Within the framework of this study, the apparatus of mechanics of deformable bodies was used to describe the state of the metal of the surface layer at the stages of the part's life cycle, including cutting, surface plastic deformation (SPD), and operational fatigue loading. This description is based on the concept of continuous accumulation of deformations and exhaustion of the plasticity margin of the metal of the surface layer of the part under the influence of loading programs at the stages of cutting, surface plastic deformation and operational fatigue loading [18-20].

When solving the problems of mechanics, the initial characteristics of the metal include hardening curve \( \sigma_s = \sigma_s(\Lambda) \), limiting plasticity curve \( \Lambda_p = \Lambda_p(\Pi) \), loading program as \( \Lambda = \Lambda(\Pi) \), degree of depletion of the plasticity margin \( \Psi = 0 \) in the initial unhardened state, and the diagram of cyclic crack resistance \( V = V(K) \), where \( \sigma_s \) – flow limit; \( \Lambda \) – shear strain rate; \( \Lambda_p \) – limiting shear strain rate for a given indicator of the stress state diagram \( \Pi \); \( K \) – stress intensity factor; \( V \) – fatigue crack growth rate.

2. Loading programs at the stages of the life cycle
As noted, for a quantitative assessment of the loading history (technological inheritance), it was proposed to use the concept of the LP. The loading program describes the accumulation of deformations under the conditions of a changing stress state of the metal of the surface layer in the plastic deformation site at each stage of loading. Thus, the loading program reveals the physical laws of the formation of the surface layer. The convenience of its use in the theory of technological inheritance lies in the fact that it has a serious scientific basis, based on the fundamental section of physics – continuum mechanics; it
has a technological meaning, since it is completely determined by technological factors; it does not contradict the existing engineering parameters of the state of the surface layer, since the degree of deformation \( \Lambda \) has a relationship with hardness, and the stress state indicator \( \Pi \) – with residual stresses; it can be used for each operation (loading stage), including mechanical tooling and subsequent operational loading, which made it possible to perform an end-to-end analysis of all stages of processing and operation of parts from a single methodological standpoint; it has a clear connection with the degree of depletion of the plasticity of the metal.

In accordance with the established regularities, when developing a generalized model of LP, it was taken:

- the metal is in its original state (not hardened);
- the loading program consists of three stages of quasi-monotonic deformation at the stages of cutting and SPD, and \( n \) stages at the step of fatigue loading (where \( n \) is the number of loading cycles);
- the accumulation of deformations in the deformation site (at each stage) occurs continuously;
- the loading program at each next stage starts from some previously accumulated deformation value;
- the change in the sign of deformation at the boundaries of the stages occurs abruptly, respectively, the numerical values of the scheme indicator change abruptly;
- the type of LP at each next stage of loading is determined by the history of loading.

For example, for the stages of cutting and SPD, the generalized model of the loading program at three stages of quasi-monotonic deformation is as follows:

\[
\Lambda_i = \frac{1}{\sigma_{\Pi} \sqrt{2\pi}} e^{-\left(\frac{(\Pi_i - \Pi_j)^2}{2\sigma_{\Pi}^2}\right)},
\]

(1)

where \( \Lambda_i \) and \( \Pi_i \) – respectively, the initial (current) values of the degree of shear strain and the scheme indicator at the stages of quasi-monotonic deformation; \( \Lambda_j \) and \( \Pi_j \) – respectively, the final values of the degree of shear strain and the indicator of the scheme at the stages of quasi-monotonic deformation; \( \sigma_{\Pi}^2 \) – variance of the scheme indicator. Initial state for unhardened metal \( \Lambda_0 = 0 \) and \( \Pi_0 \). Further adopted:

for the first quasi-monotonic stage:

\[
\begin{align*}
\Lambda_{|i=1} &= 0 \\
\Pi_{|i=1} &= -0.577 \\
\Lambda_{|j=1} &= \Lambda_1 \\
\Pi_{|j=1} &= \Pi_1
\end{align*}
\]

(2)

for the second quasi-monotonic stage:

\[
\begin{align*}
\Lambda_{|i=2} &= \Lambda_1 \\
\Pi_{|i=2} &= \Pi_1 \\
\Lambda_{|j=2} &= \Lambda_1 + \Lambda_2 \\
\Pi_{|j=2} &= \Pi_2
\end{align*}
\]

(3)

for the third quasi-monotonic stage:

\[
\begin{align*}
\Lambda_{|i=3} &= \Lambda_1 + \Lambda_2 \\
\Pi_{|i=3} &= \Pi_2 \\
\Lambda_{|j=3} &= \Lambda_1 + \Lambda_2 + \Lambda_3 \\
\Pi_{|j=3} &= -0.577
\end{align*}
\]

(4)
where indices 1, 2, and 3 refer to the corresponding quasi-monotonic stage.

The initial values of the scheme exponent and the shear strain rate certainly depend on the loading history and may differ from those accepted. Then the loading program of the first stage starts from a certain accumulated value of the shear strain rate. In accordance with this type of description, between the first and second stages, there is an abrupt change in the indicator of the stress state, which reflects a violation of the monotony of the process. As you can see, the loading program for each next stage starts with the scheme exponent corresponding to the end of the previous stage, and the deformation – from the previously accumulated level. As a result, deformation accumulates at the end of the second stage \((\Lambda_1 + \Lambda_2)\), and the third \(- (\Lambda_1 + \Lambda_2 + \Lambda_3)\).

The starting value of the scheme exponent at the first stage and the finishing value at the third stage are taken equal to \(\Pi = -0.577\). This corresponds to the concept of the beginning and end of the plastic flow of metal in a plastic deformation site, which is a characteristic of the beginning of plastic flow of material under conditions of simple compression. Depending on the type of the problem of mechanics being solved, these values may differ from those adopted in the proposed models.

The paper establishes the numerical values of the circuit indicators at the start and finish, as well as the dispersion of the scheme exponent at the corresponding stages of the loading program.

An analytical description of the loading program at the stage of fatigue loading is obtained; the numerical value of the scheme exponent is determined by the combined action of the tensors of the external load and residual stresses. In each cycle, there are several sections of quasi-monotonic deformation. Therefore, the loading program at the stage of cyclic life consists of a set of programs for loading the metal of the surface layer of the part in each cycle of fatigue loading. At the start of fatigue loading, only residual stresses act, during loading – residual and external cyclic stresses, and at the finish – only cyclic stresses. This is due to the gradual relaxation of residual stresses as deformations accumulate and the plasticity margin is depleted.

Different loading histories lead to different configurations of loading programs, which means different curvature of the lines, the slope of these lines to the coordinate axes, the range of values of the scheme exponent and the degree of deformation in each cycle.

Thus, the stage under consideration ends with the accumulation of the limiting deformation \(\Lambda_p\), complete relaxation of residual stresses and complete depletion of the plasticity margin, i.e. \(\Psi = 1\). This state corresponds to the first signs of material discontinuity in the form of defects with a size of \((0.02-0.2)\) mm. The appearance of these visible defects means the beginning of a new stage – the stage of cyclic crack resistance, which means the work of a part with a crack.

The paper provides the analytical description of the loading programs for this stage in the categories of cyclic crack resistance diagrams in the form of \(V = V(K)\).

3. Technological inheritance in the categories of loading programs

Based on the studies performed, the following possible options for taking into account the loading history (technological inheritance) in the categories of loading programs can be proposed.

The general description of the manifestation of heredity in the formation of the loading program of the \(n\)-th stage in the presence of \(n\) previous stages of loading is presented in the form:

\[
LP_n = f_n\left(LP_{n-1}\left(LP_{n-2}\left(... LP_1\right)\right)\right).
\]  

In other words, the loading program at a given quasi-monotonic stage is determined not only by the nature of the effect and accumulation of deformation at a given time, but by the entire history of the change in the function of the shear strain rate from the indicator of the stress state diagram.

It can be stated that \(LP_n\) is a functional from the load history described in the categories of loading programs, i.e.:
Studies have shown that the “older” the history, the less the influence of this loading history on the character of deformation accumulation and depletion of the plasticity margin at a given quasi-monotonic stage of loading. In this case, the peculiarity is that the loading program and the nature of the depletion of the plasticity margin at the previous loading stage have the greatest influence on the accumulation of deformations and the depletion of the plasticity margin at this stage. The role of more "ancient" stages is reduced to the influence of the total (accumulated) deformation and the degree of depletion of the plasticity margin on the formation of loading programs.

Let us formulate the general rules of technological inheritance using the concept of loading programs.

1. Technological inheritance is manifested in the formation of hereditary deformation sites at each stage of loading.

2. Technological inheritance manifests itself in the formation of hereditary loading programs depending on hereditary deformation sites, which act as a set of initial and boundary conditions in solving problems of deformation mechanics (Fig. 1).

3. The history of loading is described in program categories in the previous stages of loading.

4. Technological inheritance at each subsequent stage manifests itself through the transformation of loading programs in comparison with loading programs for a material that does not have a similar deformation history.

5. The inherited loading program "decays" in accordance with the exponential hereditary law, which manifests itself in the displacement of the LP to the region of more "rigid" loading schemes.

6. Each stage (and step) is characterized by its own rate of deformation accumulation in unreinforced material.

7. The rate of accumulation of deformations at each subsequent stage of loading "decays" (decreases) in accordance with the exponential hereditary law.

8. The set of analytical expressions for the LP rates at the previous stages constitute the core of the hereditary type functional (HTF) at this stage of loading in the categories of loading programs or the rate of depletion of the plasticity margin.

![Figure 1. Loading programs for cutting stages, SPD and fatigue loading](image_url)
9. The influence of the change rate in LP on the HTF at the early stages is significantly lower than at the previous stage.

10. Residual stress state hereditarily depends on the total (accumulated) values of the degree of deformation and the rate of depletion of the plasticity margin.

Technological inheritance in a mechanical interpretation is the interaction of various sequential loading programs with a decreasing deformation site, when the accumulation of defects at each subsequent stage occurs under conditions of more severe loading schemes than at the previous one.

The history of deformation development is a general property described in the chronology of loading programs for the metal of the surface layer of the product.

Technological inheritance is a regularity that characterizes the ability of previous loading programs to influence the formation of loading programs at subsequent stages, and being a consequence of a certain history of loading the metal of the surface layer of the product.

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