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INTENSITY OF DISLOCATION MODELS FOR THE FORMATION OF TECHNOLOGICAL RESIDUAL STRESS IN MACHINE PARTS

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Annotation

A dislocation model of the formation of technological residual stresses and an assessment of its intensity through the energy criterion of the quality of the surface layer of machine parts - the latent (stored) energy of deformation - are presented.

Аннотация

Представлена дислокационная модель формирования технологических остаточных напряжений и оценка ее интенсивности через энергетический критерий качества поверхностного слоя деталей машин - скрытую (запасенную) энергию деформации.

Annotatsiya

Texnologik qoldiq kuchlanishlarni shakllantirishning dislokatsiya modeli va uning intensivligini mashina detallarining sirt qatlami sifatining energiya mezoni - yashirin (zahiraviy) energiyasi deformatsiya orqali baholash taqdim etilgan.

Keywords

Residual micro- and macrostresses, dislocation, dislocation density, plastic deformation, structural elements, structural-energy model, latent energy, strain hardening, stress intensity.

Analytical studies of the quality parameters of the surface layer, in particular the most important parameter - residual stresses, and the construction of adequate models that describe the real process of elastoplastic deformation of metals during machining of parts, are relevant along with experimental studies. The importance of experimental research lies in proving the adequacy or inconsistency of theoretical solutions, as well as in identifying particular patterns that correspond to given experimental conditions.

The value of analytical studies, carried out taking into account reasonable assumptions and mathematical models, as well as confirmed experimentally, lies in the possibility of developing a universal approach for revealing the mechanism of formation of the quality of the surface layer of parts. This direction covers knowledge of related and interconnected disciplines (dislocation theory of solid state physics, theory of elasticity and plasticity, thermodynamics of irreversible processes, thermophysics) and aims to synthesize micro and macro ideas about plastic deformation of a metal, which is a continuous process of generation, movement and annihilation of linear imperfections crystal structure - dislocations.

All changes in physical and mechanical parameters in the surface layer of parts during contact interaction with a cutting or hardening tool occur as a result of the transformation of energy relationships in accordance with the laws of thermodynamics.

A non-uniform deformed state of the surface layer of a part can occur after non-uniform plastic deformation as a result of processing the metal or workpiece by pressure (drawing, rolling, forging), cutting (turning, grinding), surface plastic deformation (PPD - rolling with a ball or roller, shot blasting), as well as due to non-uniform plastic deformation during heating and cooling; due to inhomogeneous changes in volume during phase transformations both in the solid state (quenching, aging, carburization of steel with a solid carburizer and other physical and chemical processes), and during the inhomogeneous occurrence of phase transformations from liquid to solid state and vice versa.

Technological residual stresses arise under the simultaneous action of various factors: mechanical, thermal, and physicochemical [1,2,3]. The formation and distribution of residual macrostresses in the surface layer of parts after cutting is explained in a first approximation by the action of two factors - force (plastic deformation), which ensures the occurrence of compressive stresses, and thermal (heating of the surface layer), which causes the formation of tensile residual stresses.

During cutting and SPD processing, due to friction between the contact surfaces of the tool and the machined surface of the part, its outer surface layer is subjected to plastic tensile deformation, and the layer of material located below is stretched elastically. After the tool passes the working area, the elastically stretched inner layer tends to compress, but this is prevented by the outer plastically deformed layer. As a result, compressive stress is formed in the outer layer, and tensile stress is formed in the inner layer.

As a result of the heating that accompanies any process of plastic deformation, the outer layer of the metal tends to elongate, but this is prevented by the colder inner layer. Consequently, the first layer is subjected to compression, and the second – to tension. When the process is intensified (intense heating), the stresses on the surface can exceed the yield strength $\sigma_{т}$ of the material being processed, which will cause plastic deformation of the compressed outer layer of the metal. During subsequent cooling, the outer layer tends to shrink to a size smaller than the original one by the amount of plastic compressive strain. However, this is prevented by the elastically stressed inner layer and, as a result, residual tensile stress is formed in the outer layer, and compressive stress is formed in the inner layer.

Thus, depending on the conditions and processing modes that create the temperature-force intensity of the process, the prevailing factor can be mechanical (force), and then compressive macrostresses will appear on the surface, or thermal, then tensile macrostresses will form on the surface. This scheme will be violated if the mechanical processing process is accompanied by phase transformations leading to irreversible volumetric changes in the structural components of steels and alloys, which are sometimes a more powerful source of the formation of technological macrostresses in the surface layer than mechanical and thermal factors.

The disadvantage of the considered model of the formation of macrostresses is the conventionality of separating simultaneously acting mechanical and thermal factors, and also the fact that they do not take into account the direction of the force load on the surface layer of the part. The direction of the force load will certainly affect both the intensity of deformation and its direction, thereby causing the occurrence of both tensile and compressive residual stresses in the surface layer of the part.

Residual microstresses are caused by the presence of various structural defects in the metal, primarily linear imperfections in the form of dislocations, dislocation walls (edges of blocks and cells), which cause deformation and stress. The reason for the formation of microstresses is also the inevitable interaction of grains with each other. A real polycrystalline body (steels and alloys) has anisotropy of mechanical properties and arbitrary grain orientation, which initiates an unequal degree of deformation of neighboring grains (crystallites) and the appearance of residual microstresses in them under the influence of an external load. An increase in deformation heterogeneity is possible if neighboring grains represent different phases characterized by different physical and mechanical properties. Therefore, the occurrence of interfacial microstresses is characteristic of multiphase alloys.

Residual stresses of the third kind are balanced in even smaller volumes, comparable to a group of atoms in the vicinity of dislocations, and characterize the magnitude of static displacements of atoms from lattice sites caused by a point defect. In continuum mechanics it is shown that a point defect causes elastic deformation $\varepsilon \cong r^{-3}$ (r – is the distance to the defect).

Thus, at the grain (block) boundary, the deformation and stress from such a defect have a finite value proportional to R^{-3} (R is the size of the grain or block). Static distortions are significant only at distances comparable to interatomic distances. The deformation of the crystal lattice (displacement of atoms) in the immediate vicinity of the defect can no longer be determined by the methods of continuum mechanics, which calls into question the term “3rd kind stress” and it is more correct to speak of “static lattice distortions”.

According to academician N.N. Davidenkov, there is no physical difference between residual stresses of the first and second kind, and the stress of the first kind is the resultant of the residual stresses of the second kind. Consequently, it can be argued that residual stresses of the second kind, in turn, are the resultant stresses of the third kind.

Thus, such a consideration of technological residual stresses reflects the hierarchy of structural levels of residual stresses by analogy with the structural levels of deformations [4]. Consideration of the structural levels of deformation (stress) provides the key to describing the unified physical essence of the mechanism of plastic flow of a crystalline body. The essence of the hierarchy of structural levels (stresses) is that each structural level experiences macrodeformation (macrostress) relative to the lower level, and microdeformation (microstress) relative to the higher level.

Although significant progress has been made in describing the general picture of plastic deformation (flow theory), it nevertheless needs to be improved, both in order to bring together theoretical and experimental data in relation to the prediction of the deformation path under a given loading condition, and in order to study microdeformations and corresponding microstresses that arise in bodies during elastic-plastic deformation. The appearance of microstrains and microstresses is a consequence of the microscopic heterogeneity of the elastic and plastic properties of a polycrystal, and is also caused by imperfections in the structure of its crystal grains, that is, dislocations. In the theory of elasticity and the theory of plasticity, stresses and strains are usually averaged within elementary volumes containing a fairly large number of crystalline grains and relationships are established between the average values of stresses and strains, which are considered macroscopic.

When establishing the law of this connection, it is necessary to take into account the microscopic inhomogeneity of the field of stresses and deformations, since the work is estimated by self-balanced microstresses on their corresponding microstrains, comparable to the work of averaged stresses on averaged deformations. This conclusion is supported by numerous experiments on measuring the heat released during macroscopic uniform deformation [5]. It turned out that the mechanical equivalent of the released heat is always less than the work expended within 5–8%, depending on the degree of deformation. Consequently, in a uniformly deformed elastic-plastic body, after removing all loads, an elastic deformation field and a corresponding field of residual stresses are formed in it, the appearance of which is explained by the microscopic heterogeneity of the mechanical properties of the crystalline body.

Let us also add to the above that with homogeneity of macrodeformations and macrostresses in the sample beyond the yield point, not only elastic, but also plastic inhomogeneous microdeformations arise, which are not detected in the experiments [5], but for which, however, work is spent, apparently comparable in magnitude with the work spent on elastic residual microdeformations. Therefore, in reality, of all the work required for plastic deformation of a body, it seems that at least 10–15% should be attributed to self-balanced microstresses and corresponding microstrains.

Let's consider the structural elements (Fig.1) and the simplest diagram (Fig.2)

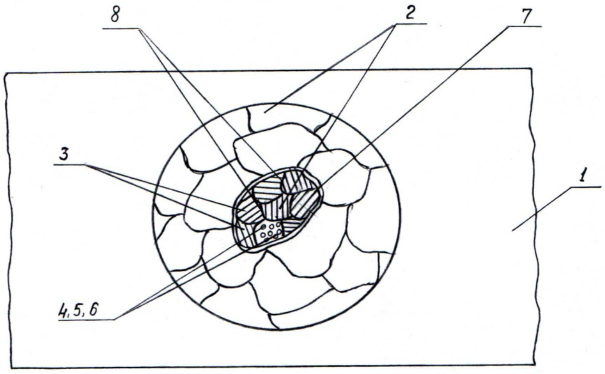


Fig.1. Structural elements of a crystalline body (metal or alloy):

1- sample; 2 – grains (crystallites); 3 – mosaic blocks;

4,5,6 – dislocations, atoms, electrons, respectively;
7 – grain boundaries; 8 – borders of mosaic blocks

In solid state physics [6], mechanical stresses in a metal or alloy, regardless of the causes that cause them (forces, temperature, high-energy particles and other factors), are considered as a consequence of distortion of the crystal lattice. Consequently, both for technological residual macrostresses and for submicroscopic ones, there can only be a single physical model of the mechanism for the formation of these stresses - the atomic or dislocation model. In other words, in order to understand and describe the nature of the plastic flow of a metal, it is necessary to analyze the dislocation structural level of the surface layer of deformable crystalline bodies during mechanical processing.

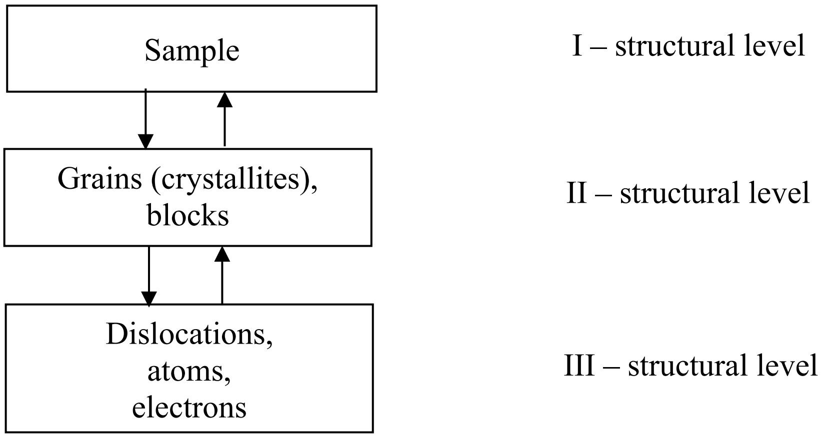


Fig.2. Hierarchy of structural levels of deformation for a polycrystalline solid

It is quite obvious that the magnitude and sign of residual macrostresses depends on the dislocation structure, characterized by the density and distribution law of dislocations, as well as other imperfections of the crystal lattice. A large accumulation of homogeneous (positive or negative) dislocations on parallel slip planes causes deformation (curvature) of the crystal lattice, leading to the formation of residual macrostresses in a given volume of the surface layer of the metal.

Residual stresses considered according to the structural-energy model [7], based on dislocation concepts of plastic deformation and the thermodynamics of contact processes during mechanical processing, should be called structural residual stresses. This name reflects the real picture of the formation of stresses from unified physical concepts based on consideration of the structural levels of deformation, and the choice of the dislocation level serves as a reliable means for synthesizing micro and macro ideas about the kinetics of the formation of residual stresses.

According to L. Klebro, D. McLean, J. Martin and other authors [8], almost all the energy stored in a crystal during its plastic deformation is accounted for by the deformation energy caused by the formed linear defects of the crystal lattice - dislocations, that is, deformation The strengthening of metals and alloys is mainly due to dislocations. The energy of point defects in the form of vacancies and interstitial atoms formed as a result of the intersection of dislocations constitutes a small fraction of the total accumulated energy. Point defects, being small in number and highly mobile, do not play a significant role in the strain hardening of metals. According to D. McLean, the relative contribution of dislocations, vacancies and interstitial atoms corresponds to the ratio 4.5: 2: 1.

Thus, the main source of latent energy accumulation is linear imperfections in the crystalline structure of the metal - a network of dislocation lines that lead to elastic distortions and, consequently, to the creation of residual stresses. Of course, there must be a correlation between residual stresses and the main parameter of dislocations—dislocation density ρ.

It should be noted that any attempts to estimate the fraction of stored energy Us for which dislocations are responsible are possible only if information about the density and distribution of dislocations is available. Experimentally, these characteristics of the fine crystal structure are directly determined by etch pits and electron microscopy methods [9].

On the basis of numerous experimental and analytical studies, V.K. Starkov [10] proposed to consider the latent energy U_s of deformation as a complex energy quality criterion for cutting. He established the influence of the level and nature of the distribution of latent energy of deformation on such physical and mechanical parameters of the state of the surface layer as microhardness, degree of strain hardening, as well as the accuracy and roughness of the treated surface. However, there is no data on residual stresses, and only hypothetically indicates a possible correlation between residual stresses and dislocation density.

The latent energy U_s is not created by elastic deformation, since after removing the deforming forces, instantaneous relaxation occurs and the internal energy returns to its original value. And only residual stresses arising as a result of plastic deformation of the metal contribute their share to the latent energy of hardening.

To study the relationship between the latent energy U_s and residual stresses σ_{res} it is necessary to rely on data on the value and distribution of dislocations in annealed and plastically deformed metal. To study the relationship between latent energy U_s and residual stresses, it is necessary to rely on data on the value and distribution of dislocations in annealed and plastically deformed metal. It has been established that annealed metals contain from 10^6 to 10^8 dislocations/sm^2, and in deformed metals the dislocation density is higher and their probable number reaches $10^{11} - 10^{12}$ per 1 sm^2. Their distribution depends on the metal and its purity, as well as on the type, degree and temperature of deformation. Their distribution depends on the metal and its purity, as well as on the type, degree and temperature of deformation.

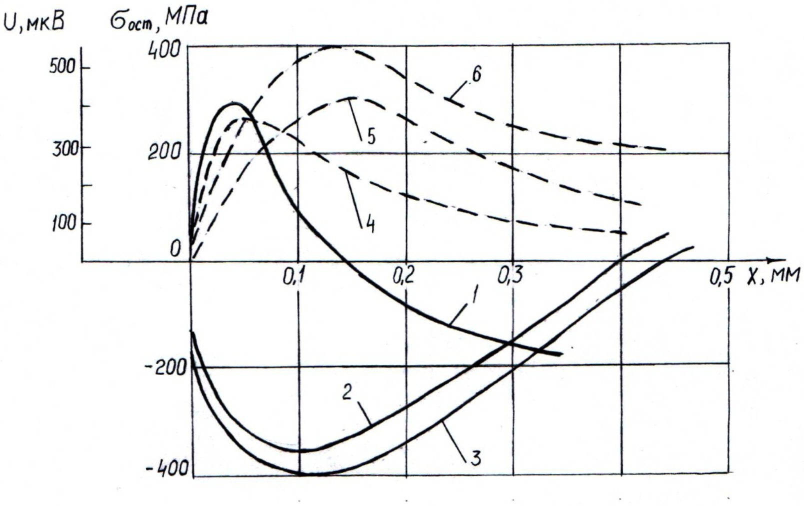


Fig.3. The influence of various methods of mechanical processing on the energy state and residual stresses in the surface layer of parts: 1.4 – turning; 2.5 – ultrasonic hardening; 3.6 – ultrasonic hardening with greater static load on the tool; ____ diagrams of residual stresses; ------ curves characterizing the level of stored (hidden) energy

The data from experimental studies by B.A. are interesting and important. Kravchenko and M.S. Nerubaya [11] to determine the latent energy of deformation in the surface layer of samples made of steel 45 after various mechanical treatments: turning, ultrasonic hardening, hardening with microballs. It has been established (Fig. 3) that the nature of the change in latent energy U_s along the depth of the surface layer is in good correlation with the level of residual stresses (macrostresses).

They also discovered a similar correlation when studying the energy state of the surface layer of a metal using exoelectronic emission methods. Since the intensity of exoelectronic emission is also associated with defects in the structure of the surface layer after strain hardening, this coincidence is apparently not accidental. It is characteristic that the maximum value of latent energy (Fig. 3) and exoelectronic emission is located at a certain depth corresponding to the maximum residual stresses.

Thus, the data presented indicate the possibility of using the latent energy U_s of deformation as an integral indicator of the quality of the surface layer of products and a scientifically grounded link in synthesizing micro- and macro-representations about the formation of technological residual stresses.

Based on comprehensive X-ray studies, J. Friedel [12] obtained an experimental relationship between stored energy and strain hardening in the form:

$$U_S \cong \frac{1}{2}\cdot\frac{E^*}{G^2}\cdot\sigma^2 \ , \qquad (1)$$

where E* is an elastic constant, the average value of which lies between the shear modulus G and the bulk compression modulus (the value of Young’s modulus E* = E is often taken); σ – average internal stress (residual stress).

Let us transform formula (1) taking into account the relationship between the shear modulus of elasticity G (modulus of elasticity of the second kind) and Young’s modulus (longitudinal elasticity E):

$$G = \frac{E}{2(1+\mu)} \ , \qquad (2)$$

where μ is Poisson's ratio.

As a result of transformations we get

$$U_S = \frac{2(1+\mu)^2}{E}\sigma^2 , \qquad (3)$$

where instead of the average internal stress σ we introduce the intensity of residual stresses σ_{res}

$$U_S = \frac{2(1+\mu)^2}{E}\sigma_{ires}^2 , \qquad (3,a)$$

from where we get the expression for it:

$$\sigma_{ires} = \frac{1}{1+\mu}\sqrt{\frac{E}{2}}\cdot\sqrt{U_S} \qquad (4)$$

or taking into account the coefficient K_σ, which takes into account the elastic properties of the deformable material:

$$\sigma_{ires} = K_\sigma\cdot\sqrt{U_S} \ , \ K_\sigma = \frac{1}{1+\mu}\sqrt{\frac{E}{2}} \qquad (4,a)$$

The transition in formula (1) from the average residual stress **?** to the residual stress intensity σ_{ires} [13] is justified by the fact that it is the stress intensity

σ_i that characterizes the stressed (including residual) state and is used in equations describing plasticity conditions, in particular, energy condition of plasticity:

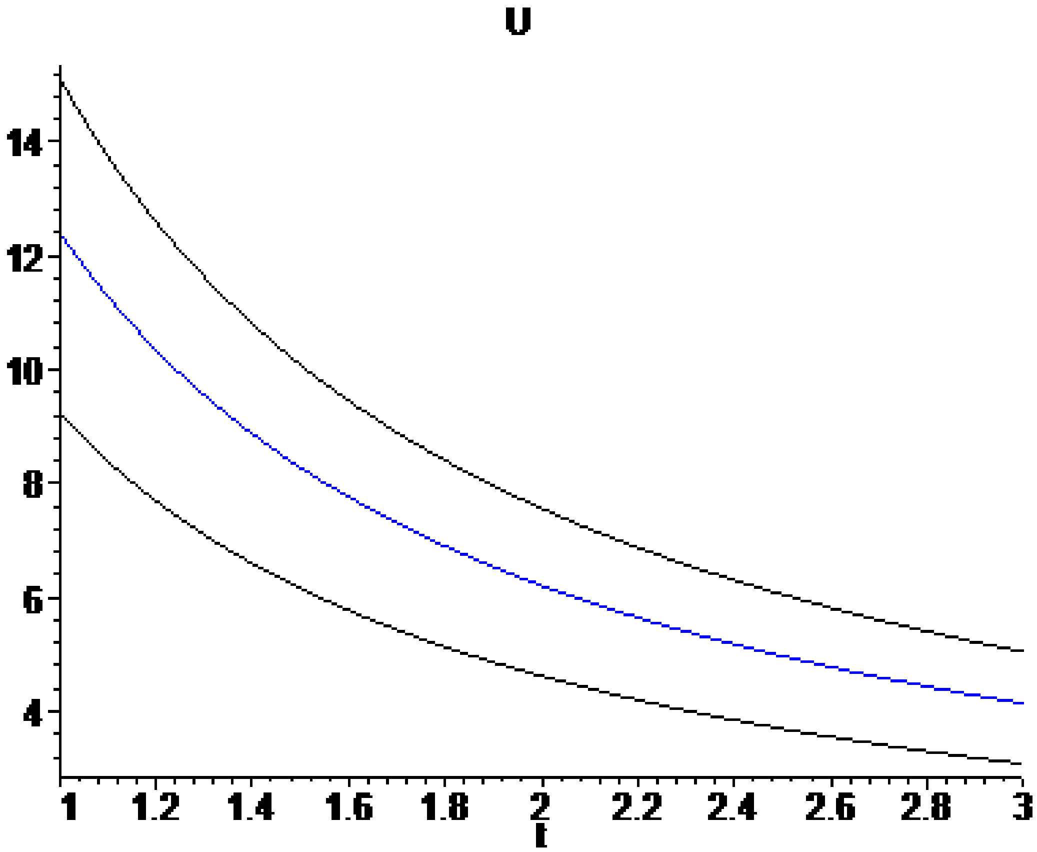
$$\sigma_i = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} = \sigma_S \,, \qquad (5)$$

Where σ_1 , σ_2 , σ_3 are the main normal stresses; σ_s – yield stress (not conditional, but true stress in a linear plastically stressed state).

Under cold deformation conditions, plastic deformation begins at $\sigma_i = \sigma_{0,2}$ (if the yield strength $\sigma_{0,2}$ is taken as the true stress). In the process of further deformation, with an increase in the degree of deformation, the yield stress σ_s due to hardening will increase, and, consequently, σ_i will increase to the required level to maintain the plastic state.

Based on the foregoing, we can conclude that knowing the nature of the distribution and the magnitude of the latent energy U_s of deformation along the depth of the surface layer and the elastic constants E and μ, it becomes possible to calculate the corresponding values of the intensity of structural residual stresses σ_{ires}, without specifying the scale of their distribution in the deformable volume of the body. Next, through the main residual stresses σ_{1res}, σ_{2res}, σ_{3res} it is necessary to determine the degree of their influence on the fatigue (endurance) of the samples for a given number of cycles of their loading.

The latent energy of deformation U_s can be determined experimentally or by less labor-intensive analytical methods, including: thermodynamic (based on the first law of thermodynamics); method based on dislocation theory; energy analysis of deformation diagrams of the processed material.



The intensity of residual stresses σ_{ires} during shot-impact strengthening of teeth of saw blades made of tool carbon steel U8G (tensile strength $\sigma_т$ =1150 MPa) was determined under the processing mode: shot speed υ=40 m/s shot diameter D=1 mm, shot consumption q=(0.75...12)·10^{-3} kgf/(sm^2·s). The calculation of the intensity of residual stresses was carried out according to the method [14], based on the structural-energy model we developed for the formation of technological residual stresses during machining of machine parts. In accordance with this technique, the following were calculated: the radius of the plastic imprint; static indentation force; normal blood pressure; velocity recovery coefficient upon impact; specific impact energy; thermal energy; stored (hidden) energy; intensity of residual stresses.

The intensity of residual stresses, depending on the mechanical properties of the material being processed and the stored energy, was determined using the modified Friedel formula, the level of which was, depending on the depth of the surface layer z:

σ_{ires}=1094 N/mm^2, z=0,05 mm; σ_{ires}=1082 N/mm^2, z=0,1 mm; $\sigma_{i\text{ост}}$=933 N/mm^2, z=0,2 mm;

The intensity values of residual stresses calculated using the above method are in good agreement with the results of experimental studies of residual stresses [15] during shot peening of cemented steel with shots with a diameter of 0.8...1 mm. Therefore, the analytical method for determining the intensity of residual stresses, taking into account the level of latent strain energy in the surface layer of parts, is a reliable means of assessing the residual stress state.

Thus, the calculation method for determining the latent energy of deformation, based on dislocation representations of the process of plastic deformation of metals during mechanical processing, creates a scientifically sound basis for establishing the relationship between the micro- and macroscopic scales of the formation of technological residual stresses in the surface layer of machine parts. Considering that among the quality parameters of the surface layer of parts that bear variable loads, residual stresses are the most important, the relevance of the proposed approach for their assessment becomes quite obvious. Data from analytical studies, confirmed experimentally, are valuable material for the development of methods for calculating and predicting the durability of critical machine parts based on the level of technological residual stresses and should contribute to the effective development of mechanical engineering technology at the present stage.

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