Chapter 2
Energy States of the Mechanothermodynamic System and the Analysis of Its Damageability

Abstract The fundamentals of the theory of evolution of mechanothermodynamic systems are developed using the energy concepts. The main feature of the theory is the analysis of damageability of material bodies due to absorption of (effective) energy caused by mechanical, thermodynamic loads, etc. The components of such energy are shown to interact dialectically. The theory of evolution of a system by damageability, as well as the fundamentals of the theory of limiting and translimiting states of a system is outlined. Particular cases of the theory of damageability are tested on experimental results.

2.1 General Notions

According to [18, 26, 37], the *mechanothermodynamic* (MTD) *system in the general case represents the thermodynamic continuum with solids distributed (scattered) within it, interacting with each other and with the continuum*. Consider its fragment of limited size $\Omega(X, Y, Z)$ shown in Fig. 2.1. The continuum has a temperature θ and a chemical composition Ch. Here there are two interacting solid elements (A and B) that can move relative to each other in the region of the contact area $S(x, y, z)$. Arbitrary mechanical loads applied to one of them (for example, to element A) in the x, y, z coordinate system can be reduced to the internal transverse forces Q_x, Q_y, Q_z, the longitudinal forces N_x, N_y, N_z and also to the bending moments M_x, M_y, M_z. Element B is pressed to element A by the loads that are reduced to the distributed normal pressure $p(x, y)$ and the tangential pressure $q(x, y)$. The origin of the coordinates is placed at the point of original contact O of the two elements (prior to volumetric deformation). It is easy to see that the elements A and B together form the *Tribo-Fatigue system* [18] which is the *friction pair* [37] *in the absence of internal forces* ($N_i = 0$, $Q_i = 0$, $M_i = 0$, $i = x, y, z$). Thus, the Tribo-Fatigue system is the *friction pair in which at least one of the elements supports non-contact loads* and, consequently, *undergoes volumetric deformation.* This representation of the MTD system has an advantage that the analysis of solid states and system components can adopt the appropriate solutions

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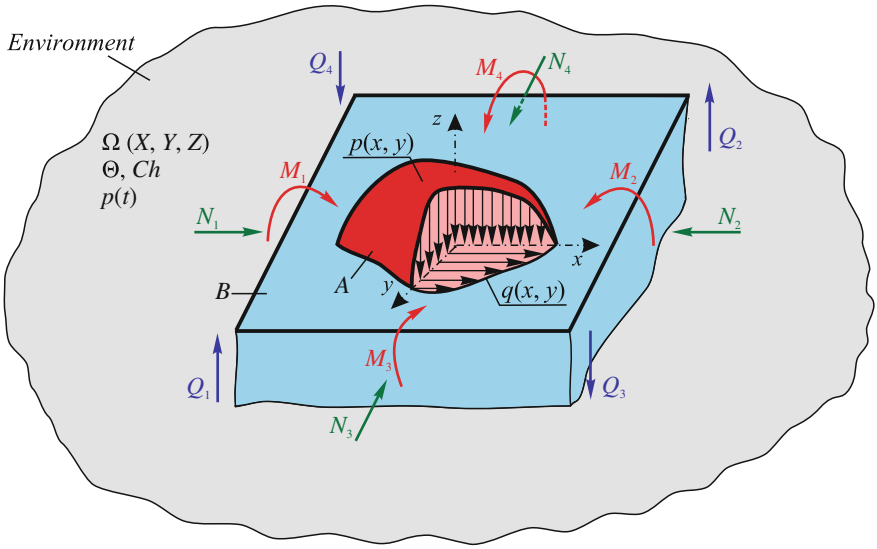


Fig. 2.1 Scheme of the elementary MTD system

known in deformable solid mechanics, in mechanics of contact interaction of solids, in mechanics of Tribo-Fatigue systems (Tribo-Fatigue), and in tribology.

Our main task is to describe the *energy state of the MTD system* under the action of mechanical and thermodynamic loads with regard to the environmental influence.

The energy state of any system is very interesting in itself. However, as applied to the MTD system it is very important to study *its damageability* and, as a result, to study the *conditions of reaching the limiting state*. Of special interest is the analysis of translimiting or supercritical conditions [37].

The main ideas, which are the fundamentals of the given theory, can be formulated considering [18, 30–32, 37] as follows.

I Due to the fact that the elements of the MTD system are subject to different-nature loads—mechanical, thermal, and electrochemical, the traditional analysis of their damageability and limiting state under the action only of mechanical stresses or strains [6, 7, 11, 13, 42, etc.] can be the basis for research. However this is not sufficient and, as a result, is ineffective. This means that there is a need to analyze MTD system states using more general —energy concepts.

II Considering that the damageability of solids of the MTD system is determined by mechanical, thermodynamic, and electrochemical loads, it is needed to introduce the *generalized representation of its complex damage* due to these loads acting at a time. Call such damage *any irreversible changes in shape, size, volume, mass, composition, structure, continuity* and,

as a result, physical-mechanical properties of the system elements. This means the corresponding *changes in the functions of the system as a whole*.

III Generation and the development of complex damage are mainly determined by means of four *particular phenomena: mechanical fatigue, friction* and *wear, thermodynamic* and *electrochemical processes.* These phenomena are called particular phenomena in the sense that each of them can be realized as independent and separate. This leads to the corresponding energy state and damage in terms of particular (separate) criteria.

IV In the *general case,* all these particular phenomena and processes in the MTD system appear *simultaneously and within one zone.* The states of such a system are then caused not by one of any mentioned phenomena, but by *their joint (collective) development and, consequently, by their interaction.*

V Damages appear and develop not at one (dangerous) point of of a loaded solid with a working volume V_0, but within its dangerous volume $V_{ij} < V_0$ having a set of points, with each of which the *critical* level of stresses (strains) is achieved or surpassed with some probability.

VI If the *physical state* of the MTD system is described by its input energy U_Σ, then the *state of its damageability* is determined only by the *effective (dangerous) part* $U_\Sigma^{eff} \ll U_\Sigma$ that is spent for generation, motion, and interaction of irreversible damages.

VII The effective energy U_Σ^{eff} under volumetric and contanct deformation of solids can be represented by the function of three energy components: *thermal* U_T^{eff}, *force* U_n^{eff}, and *frictional* U_τ^{eff}:

$$U_\Sigma^{eff} = F_\Lambda\left(U_T^{eff}, U_{n(\sigma)}^{eff}, U_\tau^{eff}\right), \tag{2.1}$$

where F_Λ takes into account the irreversible kinetic interaction of particular damage phenomena. The components $U_T^{eff}, U_n^{eff}, U_\tau^{eff}$ of the effective energy U_Σ^{eff} have no additivity.

VIII Processes of electrochemical (in particular, corrosion) damage of solids can be taken into consideration by introducing the parameter $0 \le D_{ch} \le 1$ and can be studied, for example, as *electrochemical damageability under the influence of temperature* ($D_{T(ch)}$), *stresses* ($D_{\sigma(ch)}$), *friction and corrosion* ($D_{\tau(ch)}$). So function (2.1) takes the form

$$U_\Sigma^{eff} = F_\Lambda\left(U_{T(ch)}^{eff}, U_{n(ch)}^{eff}, U_{\tau(ch)}^{eff}\right). \tag{2.2}$$

IX The *generalized criterion of the limiting (critical) state* is represented by the condition when the effective energy u_Σ^{eff} reaches its limiting value—a *critical quantity* u_0 in some area of limited size—in the *dangerous volume* of the MTD system.

X Specific energy u_0 is considered to be a *fundamental constant for a given material*. It should not depend on testing conditions, input energy types, damage mechanisms.

XI In the general case, the limiting (critical) state of the MDT system is reached not due to a simple growth of effective energy components and, hence, due to the accumulation of irreversible damages caused by individual actions (loads) of different nature, but as a result of their *dialectical interaction, whose objectives are characterized by the development of phenomena of spontaneous hardening-softening of materials* in the given operating or testing conditions.

In such a way, taking into consideration function (2.2), the *hypothesis of the limiting* (*critical*) *state of the MTD system* can be represented in the following general form

$$\Phi(u^{eff}_{n(ch)}, u^{eff}_{\tau(ch)}, u^{eff}_{T(ch)}, \Lambda_{k\backslash l\backslash q}, m_k, u_0) = 0, \tag{2.3}$$

where the m_k's $k = 1, 2, \ldots$, are some characteristic properties (hardening-softening) of contacting materials, the $\Lambda_{k\backslash l\backslash n}$'s $\gtrless 1$ are the functions (parameters) of dialectical interactions of effective energies (irreversible damages) that are caused by different-nature loads. This means that at $\Lambda_k > 1$, the damageability increase is realized, at $\Lambda_l < 1$—its decrease, and at $\Lambda_n = 1$—its stable development.

XII Based on Item III, from the physical viewpoint, hypothesis (2.3) should be multicriterion, i.e., it should describe not only the states of the system as a whole, but its individual elements in terms of different criteria of performance loss (wear, fatigue damage, pitting, corrosion damage, thermal damage, etc.). In particular cases, it is possible to reach the corresponding limiting (critical) states in terms of one or two, three or several criteria at a time.

XIII The achievement of the limiting state

$$u^{eff}_{\Sigma} = u_0 \tag{2.4}$$

means a complete loss of the integrity of the MTD system, i.e., of all its functions. At the same time, the *damageability* of its elements

$$0 < \psi^{eff}_{u} = u^{eff}_{\Sigma}/u_0 \tag{2.5}$$

reaches the critical value

$$\psi^{eff}_{u}\left(\psi_{\sigma(ch)}, \psi_{\tau(ch)}, \psi_{T(ch)}, \Lambda_{k\backslash l\backslash q}, m_k\right) = 1. \tag{2.6}$$

XIV If $t = t_0$ is the time of origination of the system and $T_{\oplus}$ is the time when the system reaches its limiting state, then the *failure time of its functions*

corresponds to the *relative life (longevity)* $t/T_{\oplus} = 1$. But the *lifetime* T_* *of the system* as the *material object* is longer than its existence time as a whole $(T_* \gg T_{\oplus})$ since at the time moment $t > T_{\oplus}$ the long process of system *degradation—disintegration* is realized by forming a great number of remains, pieces, fragments, etc. This process develops under the action of not only possible mechanical loads, but mainly under the environmental influence—up to the *system death as the material object* at the time moment $t = T_*$. The system death means its *complete disintegration into an infinitely large number of ultimately small particles* (for example, atoms). The *translimiting state of the system as a gradually disintegrating material object* can then be described by the following conditions

$$\psi_u^{eff} \to \infty; \tag{2.7}$$

$$d_\psi \to 0, \tag{2.8}$$

where d_ψ is the average size of disintegrating particles. At that, the organic relationship $\psi_u^{eff}(d_\psi)$ should exist between ψ_Σ and d_ψ. Then the *death condition* of the system is

$$t/T_* = 1. \tag{2.9}$$

XV Particles of "old system" disintegration are not destroyed, but are spent for the formation and growth of a number of "new systems". This is the essence of the *MTD system evolution hysteresis*.

2.2 Energy Theory of Limiting States

First, specify function (2.1).

To determine *speficic* effective energy, consider the *work of internal forces in an elementary volume dV of the Tribo-Fatigue system* ($A \rightleftharpoons B$ in Fig. 2.1). In the general case, the differential of the work of the internal forces and the temperature dT_Σ can be written considering the rule of expanding the biscalar product of the *stress and strain tensors* σ and ε:

$$\begin{aligned} du = \sigma_{ij} \cdot d\varepsilon_{ij} + kdT_\Sigma &= \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{pmatrix} \cdot \begin{pmatrix} d\varepsilon_{xx} & d\varepsilon_{xy} & d\varepsilon_{xz} \\ d\varepsilon_{yx} & d\varepsilon_{yy} & d\varepsilon_{yz} \\ d\varepsilon_{zx} & d\gamma_{zy} & d\varepsilon_{zz} \end{pmatrix} + kdT_\Sigma \\ &= \sigma_{xx}d\varepsilon_{xx} + \sigma_{yy}d\varepsilon_{yy} + \sigma_{zz}d\varepsilon_{zz} + \sigma_{xy}d\varepsilon_{xy} + \sigma_{xz}d\varepsilon_{xz} + \sigma_{yz}d\varepsilon_{yz} + kdT_\Sigma; \end{aligned} \tag{2.10}$$

here k is the *Boltzmann* constant.

We proceed from the idea that in the general case, according to [13], the main role in forming wear-fatigue damage is played by the normal and shear stresses that cause the processes of *shear (due to friction)* and *tear (due to tension-compression).*

In this case, it is reasonable to divide the tensor σ into two parts: σ_τ is the *tensor of friction-shear stresses* or, briefly, the *shear tensor* and σ_σ is the *tensor of normal stresses (tension-compression),* or, briefly, the *tear tensor.* So in (2.10), the tear part σ_n and the shear part σ_τ of the tensor σ will be set as:

$$\begin{aligned} du &= \sigma_{ij}^{(V,W)} \cdot d\varepsilon_{ij}^{(V,W)} + kdT_\Sigma = \left(\sigma_n^{(V,W)} + \sigma_\tau^{(V,W)}\right) \cdot d\varepsilon_{ij}^{(V,W)} + kdT_\Sigma \\ &= \sigma_n^{(V,W)} \cdot d\varepsilon_{ij}^{(V,W)} + \sigma_\tau^{(V,W)} \cdot d\varepsilon_{ij}^{(V,W)} + kdT_\Sigma = du_n + du_\tau + du_T. \end{aligned} \tag{2.11}$$

According to Items III and IV, the tensors σ and ε should be represented as follows:

$$\sigma_{ij} = \sigma_{ij}^{(V,W)} = \sigma_{ij}\left(\sigma_{ij}^{(V)}, \sigma_{ij}^{(W)}\right), \quad \varepsilon_{ij} = \varepsilon_{ij}^{(V,W)} = \varepsilon_{ij}\left(\varepsilon_{ij}^{(V)}, \varepsilon_{ij}^{(W)}\right). \tag{2.12}$$

Here, the stress and strain tensors with the superscript *V* are caused by the action of volumetric loads (the general cases of 3D bending, torsion, and tension-compression) and those with the superscript *W*—by the contact interaction of the system elements.

Expression (2.11) with regard to (2.12) can be given as follows:

$$\begin{aligned} du &= \sigma_{ij}^{(V,W)} \cdot d\varepsilon_{ij}^{(V,W)} + kdT_\Sigma = \left(\sigma_n^{(V,W)} + \sigma_\tau^{(V,W)}\right) \cdot d\varepsilon_{ij}^{(V,W)} + kdT_\Sigma \\ &= \sigma_n^{(V,W)} \cdot d\varepsilon_{ij}^{(V,W)} + \sigma_\tau^{(V,W)} \cdot d\varepsilon_{ij}^{(V,W)} + kdT_\Sigma = du_n + du_\tau + du_T. \end{aligned} \tag{2.13}$$

In the case of the linear relationship between the stresses and strains, expression (2.12) will assume the form:

$$\sigma_{ij} = \sigma_{ij}^{(V,W)} = \sigma_{ij}^{(V)} + \sigma_{ij}^{(W)} = \begin{pmatrix} \sigma_{xx}^{(V)} + \sigma_{xx}^{(W)} & \sigma_{xy}^{(V)} + \sigma_{xy}^{(W)} & \sigma_{xz}^{(V)} + \sigma_{xz}^{(W)} \\ \sigma_{yx}^{(V)} + \sigma_{yx}^{(W)} & \sigma_{yy}^{(V)} + \sigma_{yy}^{(W)} & \sigma_{yz}^{(V)} + \sigma_{yz}^{(W)} \\ \sigma_{zx}^{(V)} + \sigma_{zx}^{(W)} & \sigma_{zy}^{(V)} + \sigma_{zy}^{(W)} & \sigma_{zz}^{(V)} + \sigma_{zz}^{(W)} \end{pmatrix}, \tag{2.14}$$

$$\varepsilon_{ij} = \varepsilon_{ij}^{(V,W)} = \varepsilon_{ij}^{(V)} + \varepsilon_{ij}^{(W)} = \begin{pmatrix} \varepsilon_{xx}^{(V)} + \varepsilon_{xx}^{(W)} & \varepsilon_{xy}^{(V)} + \varepsilon_{xy}^{(W)} & \varepsilon_{xz}^{(V)} + \varepsilon_{xz}^{(W)} \\ \varepsilon_{yx}^{(V)} + \varepsilon_{yx}^{(W)} & \varepsilon_{yy}^{(V)} + \varepsilon_{yy}^{(W)} & \varepsilon_{yz}^{(V)} + \varepsilon_{yz}^{(W)} \\ \varepsilon_{zx}^{(V)} + \varepsilon_{zx}^{(W)} & \varepsilon_{zy}^{(V)} + \varepsilon_{zy}^{(W)} & \varepsilon_{zz}^{(V)} + \varepsilon_{zz}^{(W)} \end{pmatrix}, \tag{2.15}$$

and (2.13) will be as follows:

$$
\begin{aligned}
du = u &= \frac{1}{2}\sigma_{ij}\cdot\varepsilon_{ij} + kT_\Sigma = \frac{1}{2}\left(\sigma_{ij}^{(V)} + \sigma_{ij}^{(W)}\right)\cdot\left(\varepsilon_{ij}^{(V)} + \varepsilon_{ij}^{(W)}\right) + kT_\Sigma \\
&= \frac{1}{2}\left[\left(\sigma_n^{(V)} + \sigma_n^{(W)}\right) + \left(\sigma_\tau^{(V)} + \sigma_\tau^{(W)}\right)\right]\cdot\left(\varepsilon_{ij}^{(V)} + \varepsilon_{ij}^{(W)}\right) + kT_\Sigma \\
&= \frac{1}{2}\left[\begin{pmatrix} \sigma_{xx}^{(V)} + \sigma_{xx}^{(W)} & 0 & 0 \\ 0 & \sigma_{yy}^{(V)} + \sigma_{yy}^{(W)} & 0 \\ 0 & 0 & \sigma_{zz}^{(V)} + \sigma_{zz}^{(W)} \end{pmatrix} + \right. \\
&\quad \left. + \begin{pmatrix} 0 & \sigma_{xy}^{(V)} + \sigma_{xy}^{(W)} & \sigma_{xz}^{(V)} + \sigma_{xz}^{(W)} \\ \sigma_{yx}^{(V)} + \sigma_{yx}^{(W)} & 0 & \sigma_{yz}^{(V)} + \sigma_{yz}^{(W)} \\ \sigma_{zx}^{(V)} + \sigma_{zx}^{(W)} & \sigma_{zy}^{(V)} + \sigma_{zy}^{(W)} & 0 \end{pmatrix}\right] \\
&\quad \cdot \begin{pmatrix} \varepsilon_{xx}^{(V)} + \varepsilon_{xx}^{(W)} & \varepsilon_{xy}^{(V)} + \varepsilon_{xy}^{(W)} & \varepsilon_{xz}^{(V)} + \varepsilon_{xz}^{(W)} \\ \varepsilon_{yx}^{(V)} + \varepsilon_{yx}^{(W)} & \varepsilon_{yy}^{(V)} + \varepsilon_{yy}^{(W)} & \varepsilon_{yz}^{(V)} + \varepsilon_{yz}^{(W)} \\ \varepsilon_{zx}^{(V)} + \varepsilon_{zx}^{(W)} & \varepsilon_{zy}^{(V)} + \varepsilon_{zy}^{(W)} & \varepsilon_{zz}^{(V)} + \varepsilon_{zz}^{(W)} \end{pmatrix} + kT_\Sigma.
\end{aligned}
\tag{2.16}
$$

From (2.16) it is seen that the tear part σ_n of the tensor σ is the sum of the tear parts of the tensors under the volumetric deformation $\sigma_n^{(V)}$ and the surface load (friction) $\sigma_n^{(W)}$, whereas the shear part σ_τ is the sum of the shear parts $\sigma_\tau^{(V)}$ and $\sigma_\tau^{(W)}$. This means the *fundamental particularity* of the generalized approach to the construction of the criterion for the limiting state of the MTD system.

The effective part of total energy (2.16) is separated according to Items V and VIII with regard to [30–32, 37]. To do this, introduce the coefficients of appropriate dimensions $A_n(V)$, $A_\tau(V)$, and $A_T(V)$ that determine the fraction of the absorbed energy

$$
du_\Sigma^{eff} = \Lambda_{M\backslash T}(V)\left\{\Lambda_{n\backslash\tau}(V)\left[A_n(V)\sigma_n\cdot d\varepsilon_{ij} + A_\tau(V)\sigma_\tau\cdot d\varepsilon_{ij}\right] + A_T(V)kdT_\Sigma\right\},
\tag{2.17}
$$

or

$$
du_\Sigma^{eff} = \Lambda_{M\backslash T}(V)\left\{\Lambda_{n\backslash\tau}(V)[A_n(V)du_n + A_\tau(V)du_\tau] + A_T(V)du_T\right\},
\tag{2.18}
$$

where $\Lambda_{M\backslash T}(V)$ and $\Lambda_{\tau\backslash\sigma}(V)$ are the interaction functions of different-nature energies. The subscript $\tau\backslash\sigma$ means that the function Λ describes the interaction between the shear (τ) and tear (σ) components of effective energy, and the subscript $M\backslash T$ means that the function Λ describes the interaction between the mechanical (M) and thermal (T) parts of effective energy. The fact that generally speaking, the coefficients A can be different for different points of the volume V, enables one to allow for the continuum inhomogeneity. Taking into consideration (2.18), criteria (2.3) can be specified with no regard to the influence of the electrochemical properties (ch) of the environment:

$$\Lambda_{M\backslash T}(V)\left\{\Lambda_{n\backslash\tau}(V)\left[u_n^{eff}+u_\tau^{eff}\right]+u_T^{eff}\right\}=u_0. \tag{2.19}$$

In the case of the linear relationship between the stresses and strains, expressions (2.17) and (2.18) will be as follows:

$$u_\Sigma^{eff}=\Lambda_{M\backslash T}(V)\left\{\Lambda_{n\backslash\tau}(V)\left[\frac{1}{2}A_n(V)\,\sigma_n\cdot\varepsilon_{ij}+\frac{1}{2}A_\tau(V)\,\sigma_\tau\cdot\varepsilon_{ij}\right]+A_T(V)\,kT_\Sigma\right\}, \tag{2.20}$$

or

$$\begin{aligned}u_\Sigma^{eff}&=\Lambda_{M\backslash T}(V)\left\{\Lambda_{n\backslash\tau}(V)\left[A_n(V)u_n(V)+A_\tau(V)u_\tau(V)\right]+A_T(V)u(V)\right\}\\&=\Lambda_{M\backslash T}(V)\left\{\Lambda_{n\backslash\tau}(V)\left[u_n^{eff}(V)+u_\tau^{eff}(V)\right]+u_T^{eff}(V)\right\}.\end{aligned} \tag{2.21}$$

With regard to expression (2.12), criterion (2.19) can be represented as follows:

$$u_\Sigma^{eff}=\left\{\left[u_n^{eff}(\sigma_n^{(V,W)},\varepsilon_n^{(V,W)})+u_\tau^{eff}(\sigma_\tau^{(V,W)},\varepsilon_\tau^{(V,W)})\right]\Lambda_{n\backslash\tau}+u_T^{eff}\right\}\Lambda_{T\backslash M}=u_0. \tag{2.22}$$

When the time effects should be taken into consideration, criterion (2.22) will assume the form:

$$u_{\Sigma t}^{eff}=\int_0^t\left\{\left[u_n^{eff}(\sigma_n^{(V,W)},\varepsilon_n^{(V,W)},t)+u_\tau^{eff}(\sigma_\tau^{(V,W)},\varepsilon_\tau^{(V,W)},t)\right]\Lambda_{n\backslash\tau}(t)+u_T^{eff}(t)\right\}\Lambda_{T\backslash M}(t)\,dt=u_0. \tag{2.23}$$

Thus, expression (2.21) is a concrete definition of function (2.1) and formula (2.22) is a concrete definition of criterion (2.3) for that case when the electrochemical influence of the environment is not allowed for.

Criterion (2.3) in forms (2.22) and (2.23) says: *when the sum of interacting effective energy components when acted upon by force, frictional, and thermal (thermodynamic) loads reach the critical (limiting) quantity* u_0*, the limiting (or critical) state of the MTD system (of the both individual elements of the system and the system as a whole) is realized. Physically, this state is determined by many and different damages.*

The fundamental character of the parameter u_0 has been mentioned above. According to [16, 48, 49], the parameter u_0 will be interpreted as the *initial activation energy of the disintegration process.* It is shown that the quantity u_0 approximately *corresponds both to the sublimation heat for metals* and *crystals with ionic bonds* and *to the activation energy of thermal destruction for polymers,* i.e.,:

$$u_0 \approx u_T.$$

On the other hand, the quantity u_0 is determined as the *activation energy for mechanical failure:*

$$u_0 \approx u_M.$$

In such a way, the energy u_0 can be considered to be the *material constant*:

$$u_0 \approx u_M \approx u_T = \text{const}. \tag{2.24}$$

Taking into consideration the physical-mechanical and thermodynamic representations of the processes of damageability and failure [5, 8, 48], write down (2.24) in the following form:

$$u_M = s_k \frac{\sigma_{th}}{E} \frac{C_a}{\alpha_V} = u_0 = kT_S \ln \frac{k\theta_D}{h} = u_T, \tag{2.25}$$

where s_k is the reduction coefficient, σ_{th} is the theoretical strength, E is the elasticity modulus, C_a is the heat capacity of atom, α_V is the thermal expansion of volume, k is the *Boltzmann* constant, T_S is the melting point, θ_D is the *Debye* temperature, h is the *Planck* constant. According to (2.25), it can be taken approximately [48]

$$u_0 \approx \varepsilon_* \frac{C_a}{\alpha_V}, \tag{2.26}$$

where $\varepsilon_* \approx 0.6$ is the ultimate strain of the interatomic bond. Calculations according to (2.26) are not difficult. Methods of experimental determination of the quantity u_0 have also been developed [16].

From equality (2.25), it follows that u_0 is the activation energy of a given material, which is by the order of magnitude equal to 1–10 eV per one particle or molecule ($\sim 10^2$ to 10^3 kJ/mol), i.e., *the value that is close to the energy of interatomic bond rupture in the solid* [2]. Its level does not depend on how the rupture is reached—mechanically, thermally or by their simultaneous action. In [16], it is possible to find the tables containing the u_0 values for different materials.

From (2.25), it is possible to find the *thermomechanical constant of material* [37]

$$\frac{\sigma_{th}}{T_S} = E \frac{\alpha_V k}{C_a} \ln \frac{k\theta_D}{h} = \theta_\sigma. \tag{2.27}$$

The constant θ_σ characterizes the *strength loss per 1 K.*

2.3 Energy Theory of Damage

Criterion (2.22) is written in absolute values of physical parameters—in values of effective and critical energy components. This criterion can be easily made dimensionless by diving it by the quantity u_0. It can then be represented *in terms of irreversible (effective) damage*

$$\psi_u^{eff} = \frac{u_\Sigma^{eff}}{u_0} = 1. \tag{2.28}$$

It is clear that the *local (at the point) energy measure of damageability* ψ_u^{eff} varies within the range

$$0 \le \psi_u^{eff} \le 1, \tag{2.29}$$

or in detailed form

$$0 \le \psi_u^{eff} = \frac{\Lambda_{T\backslash M}}{u_0}\left\{\left[u_n^{eff}\left(\sigma_n^{(V,W)}, \varepsilon_n^{(V,W)}\right) + u_\tau^{eff}\left(\sigma_\tau^{(V,W)}, \varepsilon_\tau^{(V,W)}\right)\right]\Lambda_{n\backslash\tau} + u_T^{eff}\right\} \le 1. \tag{2.29a}$$

According to (2.29a), *particular energy measures of damageability* can also be determined:

$$0 \le \psi_n^{eff} = \frac{u_n^{eff}\left(\sigma_n^{(V,W)}, \varepsilon_n^{(V,W)}\right)}{u_0} \le 1; \tag{2.30}$$

$$0 \le \psi_\tau^{eff} = \frac{u_\tau^{eff}\left(\sigma_\tau^{(V,W)}, \varepsilon_\tau^{(V,W)}\right)}{u_0} \le 1; \tag{2.31}$$

$$0 \le \psi_T^{eff} = \frac{u_T^{eff}}{u_0} \le 1 \tag{2.32}$$

due to effective different-nature energies that are determined by force (subscripts n), frictional (subscripts τ), and thermodynamic (subscripts T) loads, respectively. Now criterion (2.28) can be written in dimensionless form

$$\psi_u^{eff} = \left[\left(\psi_n^{eff} + \psi_\tau^{eff}\right)\Lambda_{n\backslash\tau} + \psi_T^{eff}\right]\Lambda_{M\backslash T} = 1. \tag{2.33}$$

According to (2.33), the limiting state of the MTD system is reached when the sum of interacting damages $(0 < \psi < 1)$ due to mechanical and thermodynamic loads becomes equal to 1. Criterion (2.22) in form (2.33) is convenient because all damageability measures are dimensionless and are within the same range $0 < \psi < 1$.

Since numerous and infinite actions and the interaction effects of physical damages of many types (dislocations, vacancies, inelastic deformations, etc.) cannot be described and predicted exactly, when analyzing the MTD system, one introduces the concept of the *interaction of dangerous volumes* [37] that contain a real complex of damages [defects generated by the action of the corresponding fields of stresses (strains)]. According to the *statistical model of the deformable solid with the dangerous volume* [38], for example, in the case of fatigue damage of the construction element in the linear stress state, the volume should depend on its geometric parameters responsible for the working volume V_0 of the solid, on distribution function parameters $p(\sigma_{-1})$ and $p(\sigma)$ of the fatigue limit σ_{-1} and on acting stresses σ considering both the probabilities P and γ_0, as well as gradients G_σ of acting stresses:

$$V_{P_\gamma} = F_V[p(\sigma_{-1}), p(\sigma), G_\sigma, V_0, P, \gamma_0, \vartheta_V]. \tag{2.34}$$

Here, ϑ_V describes how the fatigue limit is influenced by the shape of the solid and the scheme of its loading in fatigue tests.

Thus, the *dangerous volume can serve as the equivalent of the complex of damages,* as its value is proportional, in particular to the level of effective stresses and, hence, to the number (concentrations) of defects (damages).

As follows from expression (2.34), the boundary between dangerous and safe volumes is generally blurred and probabilistic in nature. As the damage probability P of the solid increases, the dangerous volume V_{P_γ} is growing. At a given value of P, the volume can vary depending on the confidence probability γ_0. It means that at P = const

$$V_{P_{\gamma\min}} \le V_{P_\gamma} \le V_{P_{\gamma\max}}, \tag{2.35}$$

if $\gamma_{\min} \le \gamma_0 \le \gamma_{\max}$. Here, $\gamma_{\min}, \gamma_{\max}$ form the permissible range of γ_0. If it is assumed that $\gamma_0 = \text{const}$, then the dangerous volume will have a single value associated with the damage probability P.

Scattered damage within the dangerous volume is characteristic not only for the so-called smooth solids but also for the elements with structural *stress concentrators* [38]. Figure 2.2 demonstrates several microcracks in the sharp notch (rounding-off radius r = 0.5 mm, the theoretical stress concentration factor $\alpha_n = 8$ in Fig. 2.2a) and in the flat notch (r = 2 mm, $\alpha_n = 2.55$ in Fig. 2.2b) and also two fatigue cracks at a distance of 25 mm from each other at the filet joint from the crankshaft journal to its web (r = 18 mm, $\alpha_n = 3.2$ in Fig. 2.2c); the crankshaft journal diameter is 360 mm.

Thus, if in the uniaxial stress state, the stress distribution σ (x, y, z) in the x, y, z coordinates is known, then the *dangerous volume should be calculated by the formula*

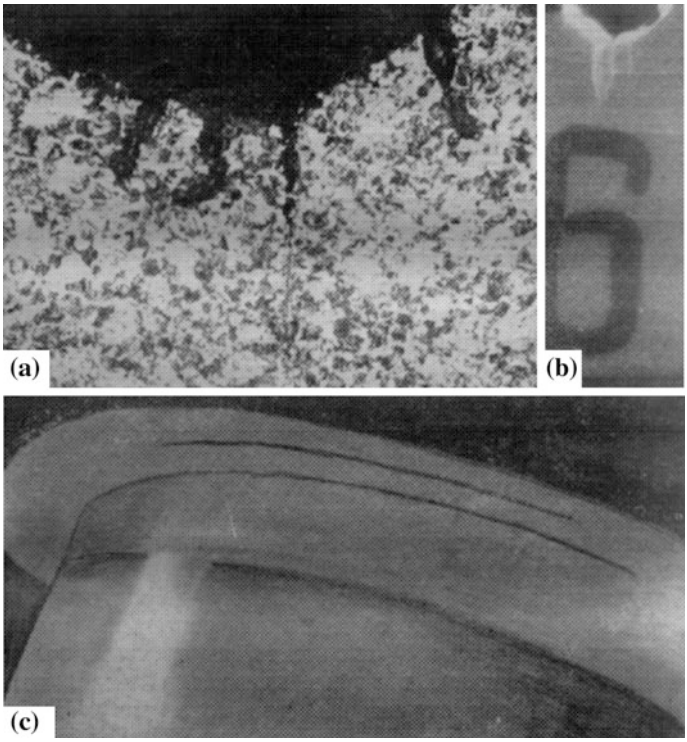


Fig. 2.2 Fatigue microcracks in the zones of stress concentrators (L.A. Sosnovskiy)

$$V_{P_\gamma} = \iiint\limits_{\sigma(x,y,z) > \sigma_{-1\min}} dxdydz, \tag{2.36}$$

Here $\sigma_{-1\min}$ being the lower boundary of the range of the fatigue limit σ_{-1} is such that if $\sigma_{-1} < \sigma_{-1\,\min}$, then $P = 0$.

From expression (2.36) it follows that the *generalized condition for fatigue failure* is of the form

$$V_{P_\gamma} > 0 \tag{2.37}$$

with some probability P under the confidence probability γ_0.

If

$$V_{P_\gamma} = 0, \tag{2.38}$$

then physically, fatigue failure cannot occur (as in this case, $\sigma < \sigma_{-1\min}$); hence, (2.38) is the *generalized condition of no-failure.*

The methods for calculation of dangerous volumes V_{ij} for friction pairs and Tribo-Fatigue systems are developed similar to (2.34)

$$V_{ij} = V_{ij}\left(\sigma_n^{(V,W)}, \sigma_\tau^{(V,W)}, \sigma_{\lim}^{(V,W)}, G_{\sigma_{ij}}, V_0, P, \gamma_0\right) \tag{2.39}$$

and outlined elsewhere in [18, 19, 46, 47]. Here, $\sigma_{\lim}^{(V,W)}$ is the limiting stress based on an assigned criterion of damage and failure. Further, the following dimensionless damageability characteristics can be introduced: *integral energy damageability within the dangerous volume*

$$\Psi_u^{eff}(V) = \iiint\limits_{\psi_u^{eff}(dV) \geq 1} \frac{u_\Sigma^{eff}}{u_0} dV \tag{2.40}$$

and *the mean energy damageability (at each point of the dangerous volume)*

$$\bar{\Psi}_u^{eff}(V) = \frac{1}{V_u} \iiint\limits_{\psi_u^{eff}(dV) \geq 1} \frac{u_\Sigma^{eff}}{u_0} dV. \tag{2.41}$$

The *accumulation of energy damageability in time within the dangerous volume* is described by the formulas

$$\Psi_u^{eff}(V, t) = \int\limits_t \iiint\limits_{\psi_u^{eff}(dV) \geq 1} \frac{u_\Sigma^{eff}}{u_0} dVdt, \tag{2.42}$$

$$\bar{\Psi}_u^{eff}(V, t) = \int\limits_t \frac{1}{V_u} \iiint\limits_{\psi_u^{eff}(dV) \geq 1} \frac{u_\Sigma^{eff}}{u_0} dVdt. \tag{2.43}$$

Having (2.38)–(2.43), the damageability of the MTD system can be described and analyzed using the most general representations—energy concepts with regard to the influence of numerous and different factors taken into account by (2.34), including the *scale effect,* i.e., the changes in the size and shape (mass) of system elements.

According to [1, 37], the function $\Lambda_{k/l/n}$ for damage interactions in the MTD system is determined by the parameters ρ of the effective energy ratio:

$$\Lambda_{k\backslash l\backslash q} = \Lambda_{k\backslash l\backslash q}\left(\rho_{M\backslash T}, \rho_{n\backslash \tau}\right) \gtrless 1; \tag{2.44}$$

$$\rho_{n\backslash\tau} = u_\tau^{eff} / u_n^{eff}, \quad \rho_{M\backslash T} = u_M^{eff} \Big/ u_T^{eff}. \tag{2.45}$$

The quantities Λ calculated by (2.44) describe the influence of the level of load parameter ratios on the character and direction of interaction of irreversible damages. *If* $\Lambda > 1$, then the *system is self-softening* because at balance of hardening-softening phenomena, softening processes are dominant. *If* $\Lambda < 1$, then the *system is self-hardening,* because at balance of hardening-softening phenomena, hardening processes are dominant. At $\Lambda = 1$, the *system appears to be stable*—the *spontaneous hardening-softening phenomena are at balance within it.* The general analysis of damage interactions in the MTD systems will be given below (see Chap. 3).

2.4 Account of Electrochemical Damageability

After criterion (2.3) has been formalized in principle, the action of electrochemical loads (damages) should be taken into consideration according to Item VII. It should be said at once that this is difficult to perform in the strict mechanothermodynamic statement: electrochemical reactions at environment-deformable solid interactions are very diverse, complex and are insufficiently studied. That's why, the approach proposed in [30–32, 37] is adopted here: the simplification is introduced, according to which the damageability of solids in the environment is determined by corrosion-electrochemical processes. In addition, the *hypothesis is put forward, following which the effective energy of corrosion-electrochemical damage is proportional to the square of the corrosion speed*, i.e.,

$$u_{ch}^{eff} \sim v_{ch}^{2}. \tag{2.46}$$

If according to Item VII, $0 \le D_{ch} \le 1$ is the parameter of corrosion-electrochemical damage of the solid, then based on [28], criterion (2.2) with regard to (2.22) will be as follows:

$$\Lambda_{M\backslash T}\left[\left(\frac{u_n^{eff}\left(\sigma_n^{(V,W)},\varepsilon_n^{(V,W)}\right)}{u_0(1-D_n)}+\frac{u_\tau^{eff}\left(\sigma_\tau^{(V,W)},\varepsilon_\tau^{(V,W)}\right)}{u_0(1-D_\tau)}\right)\Lambda_{n\backslash\tau}+\frac{u_T^{eff}}{u_0(1-D_T)}\right]=1,\quad \Lambda\gtrless 1, \tag{2.47}$$

where

$$0 \le \frac{u_n^{eff}\left(\sigma_n^{(V,W)},\varepsilon_n^{(V,W)}\right)}{u_0(1-D_n)} = \psi_{n(ch)}^{eff} \le 1; \tag{2.48}$$

$$0 \le \frac{u_{\tau}^{eff}\left(\sigma_{\tau}^{(V,W)}, \varepsilon_{\tau}^{(V,W)}\right)}{u_0(1-D_{\tau})} = \psi_{\tau(ch)}^{eff} \le 1; \tag{2.49}$$

$$0 \le \frac{u_{T}^{eff}}{u_0(1-D_{T})} = \psi_{T(ch)}^{eff} \le 1; \tag{2.50}$$

$$1 - D_T = b_{e(T)}\left(\frac{v_{ch}}{v_{ch(T)}}\right)^{m_{v(T)}}; 1 - D_n = b_{e(n)}\left(\frac{v_{ch}}{v_{ch(n)}}\right)^{m_{v(n)}}; \\ 1 - D_{\tau} = b_{e(\tau)}\left(\frac{v_{ch}}{v_{ch(\tau)}}\right)^{m_{v(\tau)}}, \tag{2.51}$$

where v_{ch} is the corrosion speed in this environment, $v_{ch(T)}$, $v_{ch(\sigma)}$, $v_{ch(\tau)}$ is the corrosion speed in the same environment under thermal, force, and friction actions, respectively; the b_e's are the coefficients responsible for corrosive erosion processes; the $m_{V(\cdot)}$'s are the parameters responsible for the electrochemical activity of materials at force (the subscript σ), friction (the subscript τ), and thermodynamic (the subscript T) loads, wherein $m_{V(\cdot)} = 2/A_{ch}$ and the parameter $A_{ch} \gtreqless 1$.

In [12], other methods for assessment of the parameter D_{ch} can be found.

As seen, Eq. (2.47) is a specific definition of criterion (2.3). According to this criterion, the *limiting state of the MTD system is reached when the sum of dialectically interacting effective damages due to force, friction, and thermodynamic loads* (*including electrochemical damage when acted upon by stress, friction, temperature*) *becomes equal to unity*.

2.5 Some Special Cases

Further, consider the specific case when in (2.21) it is assumed that $A_{\sigma}(V) = A_{\sigma} = \text{const}$, $A_{\tau}(V) = A_{\tau} = \text{const}$, $A_T(V) = A_T = \text{const}$, $A_{\tau\backslash\sigma}(V) = A_{\tau\backslash\sigma} = \text{const}$, $A_{M\backslash T}(V) = A_{M\backslash T} = \text{const}$.

In this case, firstly, the stress state is caused by volumetric deformation, for which all stress tensor components, except one component σ (one-dimensional tension-compression, pure bending), can be neglected. Secondly, the stress state is caused by surface friction, for which all stress tensor components, except one component τ_w, can be ignored. Then (2.21) assumes the following form:

$$\Lambda_{M\backslash T}\left[\Lambda_{n\backslash\tau}\left(A_n\sigma^2 + A_{\tau}\tau^2\right) + A_T T_{\Sigma}\right] = u_0,$$

or in accordance with (2.47)

$$\Lambda_{M\backslash T}\left[\frac{a_T}{1-D_T}T_{\Sigma} + \Lambda_{n\backslash\tau}\left(\frac{a_n}{1-D_n}\sigma^2 + \frac{a_{\tau}}{1-D_{\tau}}\tau_w^2\right)\right] = u_0, \quad \Lambda \gtreqless 1, \tag{2.52}$$

where $\frac{a_n}{1-D_n} = A_n$, $\frac{a_{\tau}}{1-D_{\tau}} = A_{\tau}$, $\frac{a_T}{1-D_T} = A_T$.

Thus, Eq. (2.52) is the simplest form of the energy criterion of the limiting state that is nevertheless of great practical importance [37].

If there is no electrochemical influence of the environment ($D_{ch} = 0$), then

$$u_{\Sigma}^{eff} = \Lambda_{M\backslash T}\left[a_T T_{\Sigma} + \Lambda_{n\backslash\tau}\left(a_n\sigma^2 + a_\tau\tau_w^2\right)\right] = u_0, \quad \Lambda \gtrless 1 \tag{2.53}$$

Equation (2.53) is the simplest form of the energy criterion of the limiting state that is of great practical importance [1, 37, 43]. It serves particularly for the development of methods of assessing the parameters a_T, a_σ, a_τ. In fact, at $\Lambda_{M\backslash T} = \Lambda_{\tau\backslash n} = 1$, the boundary conditions are the following:

$$\left.\begin{aligned} T_{\Sigma} = 0,\ \tau_w = 0: &\quad a_n\sigma_d^2 = u_0, \quad a_n = u_0/\sigma_d^2; \\ T_{\Sigma} = 0,\ \sigma = 0: &\quad a_\tau\tau_d^2 = u_0, \quad a_\tau = u_0/\tau_d^2; \\ \sigma = 0, \tau_w = 0: &\quad a_T\sigma_d = u_0, \quad a_T = u_0/T_d, \end{aligned}\right\} \tag{2.54}$$

where σ_d, τ_d are the normal and friction limiting stresses as $T \to 0$. These are called (mechanical) destruction limits, T_d is the destruction temperature (when $\sigma = 0$, $\tau_w = 0$) or the thermal destruction limit [28].

The effective ("dangerous") part of total strain energy can also be determined from the following physical considerations. It shall be assumed that the *strain energy flow* u generated in the material sample subject to its strain cycling ($\varepsilon = \varepsilon_{\max}\sin\omega t$) in the homogeneous (linear) stress state is to a certain extent *similar to the light flux*. In fact, it is continuously excited when the loading cycle is repeated at the frequency $\omega = 1/\lambda$. This permits one to consider it as a wave (with a length λ). Some part of the energy u generated in such a way can be absorbed by material atoms and structural formations, followed by the material damage. Denote the absorbed part of the energy as u^{eff}. The generated energy u is then equal to:

$$u = u^{eff} + u_{cons}, \tag{2.55}$$

Here, u_{cons} is the non-absorbed part (here it is called the conservative part) of the generated energy u.

If the analogy of light and strain energy is justified, then the strain absorption law may be similar to Bouguer's light absorption law. Consequently, the equation relating the energy u_{cons} passed through the deformed material volume V and the generated energy u is of the form:

$$u_{cons} = u\exp(-\chi_\varepsilon V), \tag{2.56}$$

or, in accordance with *Lambert*, in differential form:

$$\frac{du}{u} = -\chi_\varepsilon V. \tag{2.57}$$

Here, as in *Bourguer-Lambert's* equation, the coefficient χ_ε independent of u is the energy absorption parameter.

Taking into account (2.56) in (2.55), the *absorption law* of *strain energy* is obtained:

$$u^{eff} = u[1 - \exp(-\chi_\varepsilon V)], \tag{2.58}$$

and, hence, if $u = 0$ or $V = 0$, then $u^{\text{eff}} = 0$. If $V \to \infty$, then it appears that according to (2.56), $u_{cons} = u$, i.e., all supplied energy is dissipated within such a volume.

From the physical point of view, the strain energy absorption process is caused by many phenomena:

- electron transition in absorbing atoms from lower to higher energy levels (quantum theory [9]);
- generation and development of dislocation structures (dislocation theory [4]);
- emergence of II and III order residual strains (stresses) (elasticity theory [41]);
- formation and development of any imperfections (defects) of material composition and structure—point, planar, and spatial (physical materials science [20]);
- hardening-softening phenomena (including strain aging) developing in time (fatigue theory [43]);
- changes in (internal) Tribo-Fatigue entropy (wear-fatigue damage mechanics [37]).

It should be noted that approach (2.58) can also be extended to the case of friction, since any indenter drives a strain wave upstream in the thin surface layer of the solid to which the indenter is pressed to [40]. In this case, χ_γ will be the energy absorption parameter. The subscript γ denotes the shear strain. Similarly, heat absorption in the deformable solid can also be considered. Finally, the problem of strain energy absorption in the inhomogeneous (including complex) stress state can be easily solved by setting the dangerous volume $V = V_{P_\gamma}$ into (2.56)–(2.58).

It should be noted that *although criterion* (2.53) *is particular, it is fundamental and general in nature.* Its general nature is caused by the fact that in this case, all four particular phenomena responsible for the MTD system state (in the statement simplified in terms of the stress-strain state) are taken into account (in accordance with Item III). Its fundamental nature is that here, as in complete solution (2.21), $\Lambda_{n\backslash\tau}$ takes into account the interaction of mechanical components of effective energy due to friction τ_w and normal σ stresses, whereas $\Lambda_{M\backslash T}$ takes into account the interaction of thermal and mechanical components of effective energy. The thermal component of effective energy is determined through the variations of the total temperature $T_\Sigma = T_2 - T_1$ in the zone of force contact caused by all sources of heat, including the one released during mechanical (spatial and surface) deformation, structural changes, etc.

From (2.53) it is easy to obtain a number of formulas important for application. So, the conditions of purely thermal (or thermodynamic) failure (when $\sigma = 0$ and $\tau_w = 0$) or purely mechanical failure (when $T_\Sigma \to 0$) will be as follows:

$$a_T T_\Sigma = u_0; \tag{2.59}$$

$$\Lambda_{n\backslash\tau}\left(a_n\sigma^2 + a_\tau\tau_w^2\right) = u_0. \tag{2.60}$$

For *isothermal mechanical fatigue* (when $\tau_w = 0$), we have

$$\Lambda_{M\backslash T}\left(a_T T_\Sigma + a_n\sigma^2\right) = u_0, \tag{2.61}$$

and for *isothermal frictional fatigue* (when $\sigma = 0$), we obtain

$$\Lambda_{M\backslash T}\left(a_T T_\Sigma + a_\tau\tau_w^2\right) = u_0. \tag{2.62}$$

The general analysis of the above-described partial criteria allows three main conclusions to be made.

(1) The growth of load parameters (σ, τ_w, T_Σ, D) results in a corresponding acceleration to achieve the limiting state (u_0).
(2) The limiting state of the system can also be reached by increasing only one (any) of the load parameters (other parameters remain unchanged).
(3) If $\Lambda > 1$, then the damageability of the system accordingly enhances (i.e., the processes of its softening are dominant), and if $\Lambda < 1$, then it slows down (i.e., the processes of its hardening are advantageous) in comparison with the damageability due to the joint action of load parameters alone (with no regard to the dialectical interaction of irreversible damages).

The last conclusion is also the result of a fundamentally new approach to the construction of the criterion of the limiting state of MTD systems [22]. According to this approach, *nonreciptocal influence of factors, but the interaction* ($\Lambda \gtrless 1$) *of phenomena determines the damageability processes in the MTD system* [22, 25–27, 45]. In this regard, the results of more than 600 diverse experimental data were analyzed and synthesized. This permitted the generalized MTD function of states critical for damageability to be revealed.

2.6 Analysis of Experimental Results

Experimental analysis of generalized criterion (2.47) of the limiting state of a MTD system is extremely difficult as there are no relevant experimental data. Data acquisition is though very relevant, but at the same time is very difficult and expensive. Therefore, the analysis of particular criterion (2.61) is given below.

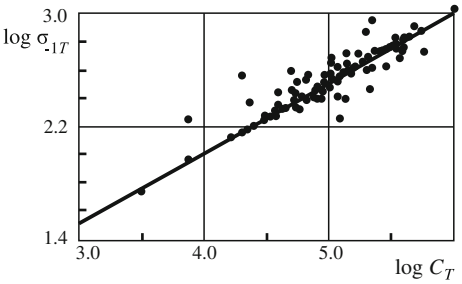


Fig. 2.3 Fatigue limits of constructional steels versus the parameter C_T (A.V. Bogdanovich, L.A. Sosnovskiy)

From (2.61) it follows that

$$\lg \sigma_{-1T} = \frac{1}{2} \lg C_T; \quad C_T = \left[u_0 / \Lambda_{M\backslash T} - a_T T_\Sigma \right] \cdot \frac{1}{a_n} \tag{2.63}$$

According to (2.63), the dependence of limiting stresses on the *parameter of thermomechanic resistance* C_T in the double logarithmic coordinates must be a straight line with the angular coefficient (1/2). The general regularity is as follows: *the higher the value of the parameter* C_T, *the greater is the quantity* σ_{-1T}. Figure 2.3 illustrates a convincing evidence of this dependence for numerous different-grade steels tested for fatigue in different conditions [1, 23, 28]. It is seen that the C_T values vary by more than two orders of magnitude, i.e., by a factor of 100 or more, and the σ_{-1T} values—by more than two orders of magnitude, i.e., by a factor of 10 or more, thus the testing temperature ranged from the helium temperature to $0.8T_s$ (T_S is the melting point). As shown in Fig. 2.3, Eq. (2.63) adequately describes the results of more than 130 experiments.

Equation (2.63) is also analyzed for different-class metal materials using the fatigue test results obtained by many authors and illustrated in Fig. 2.4a. In [43], it is possible to find a list of literature references.

In Fig. 2.4b the similar analysis is made using the tension test results at different temperatures (σ_{uT} is the strength limit). In this case, it is assumed that $\sigma_{-1} = \sigma_{uT}$ in Eq. (2.63). It is obvious: the correlation coefficient is very high—not less than $r = 0.722$ (very occasionally), but in most cases it exceeds $r = 0.9$; the analysis includes more than 300 test results. Works [1, 43] contain other examples of a successful experimental approval of criterion (2.63). This allows us to hope that even more general criteria [for example, Eqs. (2.52), (2.53), (2.60)] will be practically acceptable. In our opinion, further studies must confirm our hope.

As defined above, criterion Eq. (2.60) is valid for $\sigma \leq \sigma_u$. Depending on the test conditions, τ_W can be interpreted as the greatest contact pressure (p_0) in the center of the contact area under rolling. It can also be interpreted as the sliding stress (τ_w) or as the average (nominal) sliding pressure p_a in the contact zone, or as the fretting contact pressure (q). If the value $\sigma = \sigma_{-1}$ is fixed, where $\sigma_{-1} \ll \sigma_u$, then

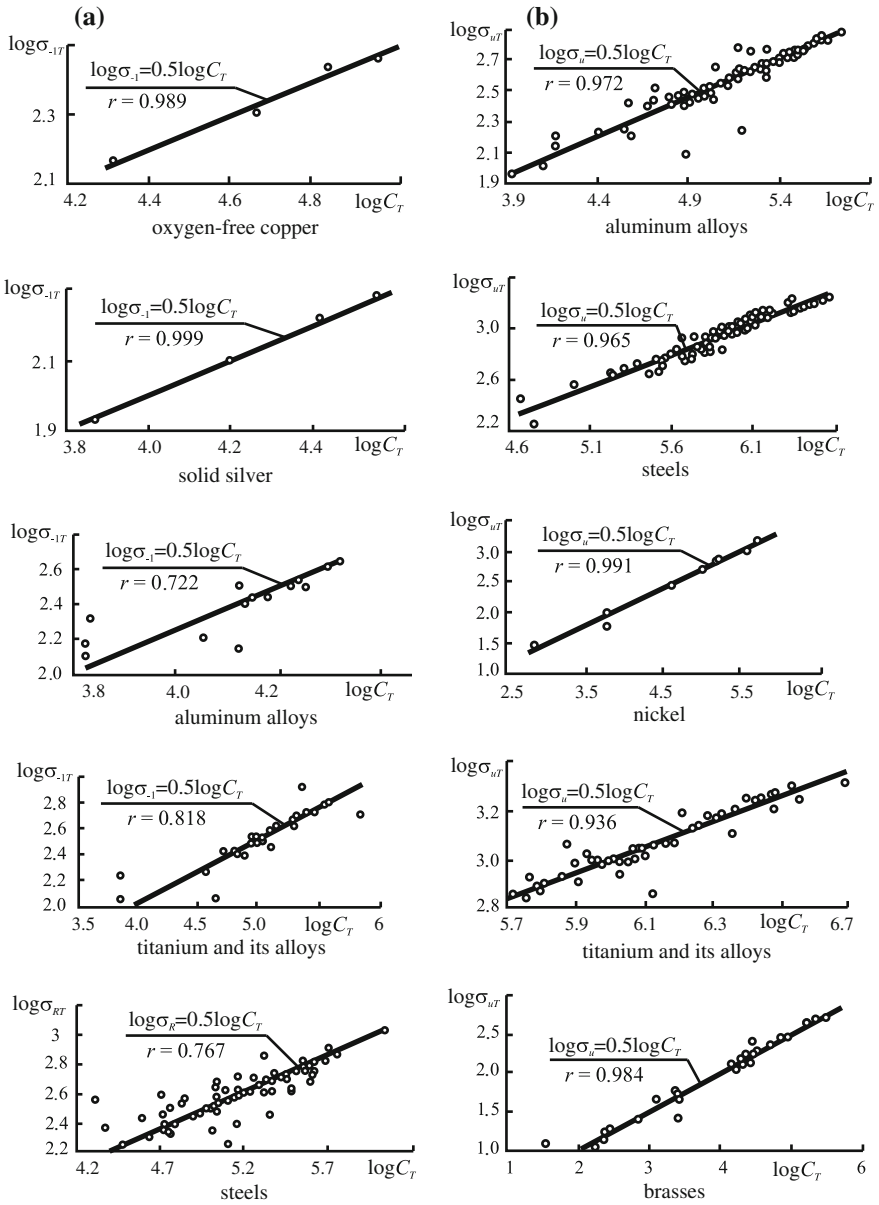


Fig. 2.4 Dependences **a** $\sigma_{-1}(C_T)$ and **b** $\sigma_u(C_T)$ for various metal materials (A.V. Bogdanovich, L.A. Sosnovskiy)

Eq. (2.60) can be represented in the form of the diagram of the limiting states of Tribo-Fatigue systems [1, 28, 37] (Fig. 2.5). The above-mentioned diagram clearly shows the zones of realization of spontaneous hardening-softening processes

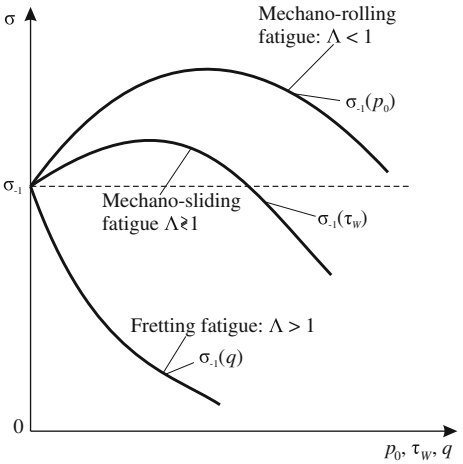


Fig. 2.5 Diagram explaining the basic features of Λ-interactions in the Tribo-Fatigue system

($\Lambda \gtrless 1$). Figure 2.5 yields the above-mentioned obvious conclusions: if $\Lambda < 1$, then we are dealing with a self-hardening system (during testing or operation under given conditions); if $\Lambda > 1$, then a system turns to be self-softening; if it is found that $\Lambda < 1$ converts to $\Lambda > 1$, then it implies that owing to the changes in the governing conditions of operation or use, the hardening processes are replaced by the softening processes.

Additional experimental support for these conclusions is shown in Figs. 2.6, 2.7 and 2.8. Note that for spontaneous hardening (for $\Lambda < 1$, Figs. 2.5, 2.6 and 2.7), it appears that *the limiting stress in wear-fatigue tests is higher than in routine fatigue tests. It means that in these conditions the processes of friction and wear become "useful"*. There are numerous works (for example, [24]), according to which dosed wear in real Tribo-Fatigue systems (for example, wheel/rail system) causes their fatigue strength to grow. At $\Lambda \gg 1$ (in Fig. 2.8), vice versa, this leads to a strong acceleration of damageability: the fatigue limit decreases with increasing the

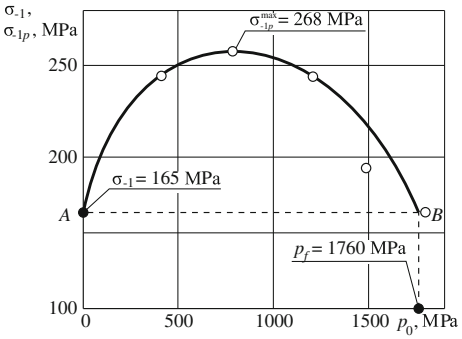


Fig. 2.6 Influence of rolling friction processes on the resistance of mechano-rolling fatigue during tests of the Tribo-Fatigue steel 45 (shaft)/steel 25 HGT (roller) system (L.A. Sosnovskiy, S.A. Tyurin)

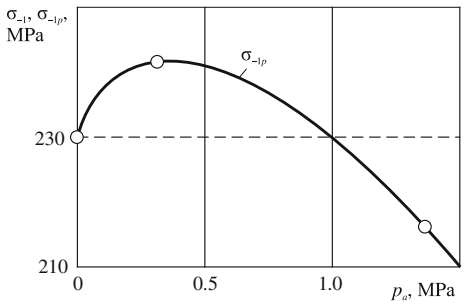


Fig. 2.7 Limiting stresses versus the contact pressure for the Tribo-Fatigue steel 45 (shaft)/cast iron (partial bearing insert) system (V.I. Pokhmursky et al.)

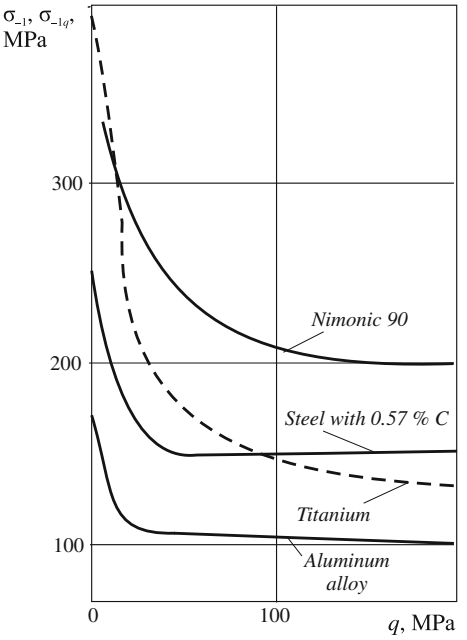


Fig. 2.8 Contact pressure versus changes in the fatigue limit at fretting fatigue according to R.B. Waterhouse (nimonic-90—*Harris W.J.*; steel with 0.5 % C—*Peterson R.E.*; titanium—*Sinclair G. M., Liu H.W., Corten H.T.*; aluminum alloy—*Corten H.T.*)

contact pressure q by a factor of 2–3. In addition, there are many works (for example, [17]), according to which the system wear yields a sharp drop in fatigue strength.

The elements of the theory of Λ-interactions of irreversible damages in active systems are formulated to the present time and are developed to some extent [29–32, 35]. Their physical picture is shown in Figs. 2.9, 2.10 and 2.11 according to

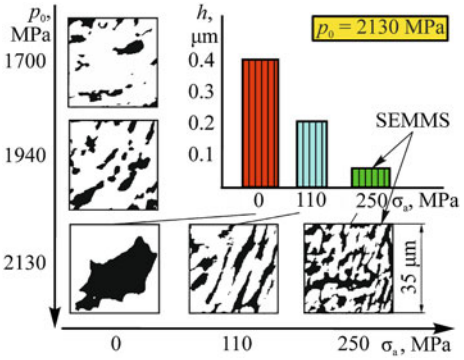


Fig. 2.9 Damage interactions at the submicrolevel: the microtopography of surface damage at rolling friction (*vertical column of pictures*) and mechano-rolling fatigue (*horizontal line of pictures*) (L.A. Sosnovskiy, S.A. Chizhik)

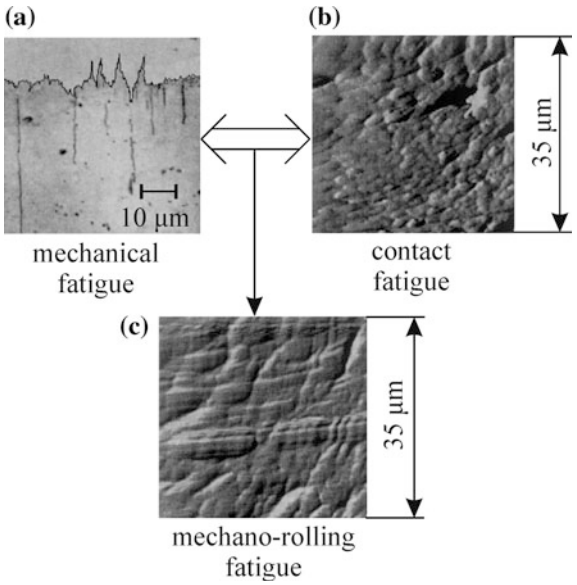


Fig. 2.10 Microlevel: the result **c** of the irreversible interactions of surface damages **a**, **b** due to mechano-rolling fatigue

experimental results [3, 26]. As shown in Fig. 2.9, the increase in the contact pressure results in the formation of pitting cavities oriented at roller paths; at p_0 = 2130 MPa their depth reaches 0.4 μm (histogram in the right upper corner). But when in the friction pair the shaft additionally undergoes bending, the damage picture substantially changes even at small cyclic stress values (σ_a = 110 MPa). In what follows, long and deep pitting cavities are not formed. This is the result of interaction of damages caused by different loads—contact and bending.

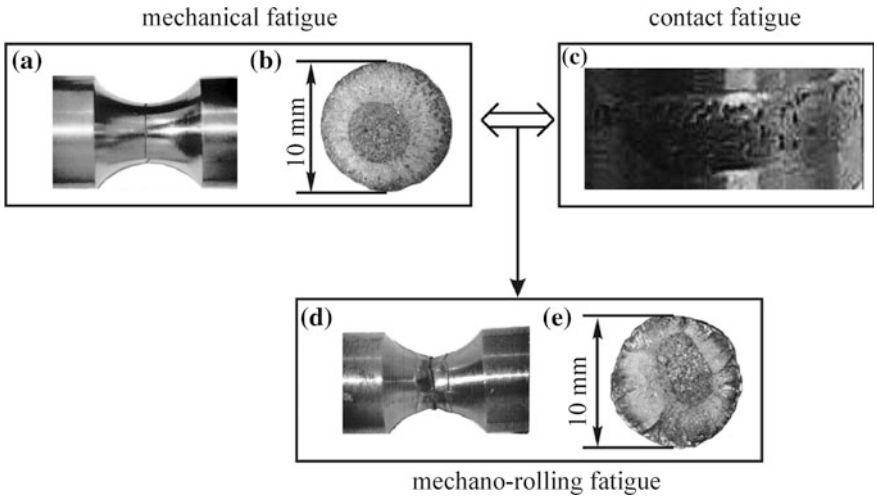


Fig. 2.11 Macrolevel: the result **c**, **d** of the irreversible interactions of shaft damages **a**, **b**, **c** due to mechano-rolling fatigue

Increasing the amplitude of cyclic stresses accelerates the process of formation of the second system of cracks—transverse to the rolling direction. As a result, damage becomes dispersed, there appears almost an equilibrium network of intersecting crack-pores which borders with fine dispersed particles (grain fragments) of material. The higher the cyclic stresses, the smaller and thinner are the separated particles, and the critical depth of a damaged layer decreases to 0.05 μm. Thereby, large and deep pitting cavities are not formed. *Surface crumbling appears to be the dominant process in this case*. It is characterized by the separation of fine dispersed particles from the working surface that are formed due to a multiple shift in intersecting planes, by the formation of a great number of microscopic crack-pores, and by the fine grinding of grains. Such a mechanism of complex surface damage is called the *scattered effect of a multiple microshift* (SEMMS) [34]. It is *Sosnovskiy–Makhutov–Chzhik's effect*.

In Fig. 2.10 it is seen that if at mechanical fatigue over the surface extrusions and intrusions are formed, whereas at contact fatigue the oriented grain topography of surface damages is formed, then in the case of mechano-rolling fatigue (due to corresponding damage interactions) another type of degradation is formed: the broken picture of multiple microshifts intersecting in two planes.

Integrally similar interactions also form the fundamentally different microstructure of fracture (Fig. 2.11).

Tables 2.1 and 2.2 summarize the physical signs of different (often encountered in practice) features of the limiting state that can find use in the corresponding research areas.

Table 2.1 Main physical signs of the limiting state

State		Condition of reaching the limiting (critical) state
Symbol	Physical state and its characteristic	
M	Mechanical state σ_{ij}	$u_n^{eff} \xrightarrow{\sigma_{ij} \to \sigma_{\lim}} u_0$
T	Thermodynamic state T_Σ	$u_T^{\text{eff}} \xrightarrow{T_\Sigma \to T_S} u_0$
MTD	Mechanothermodynamic state σ_{ijT}, T_Σ	$u_\Sigma^{eff} \overset{\sigma_{ijT} \to \sigma_{\lim}(T)}{\underset{T_\Sigma \to T_S}{\Longrightarrow}} u_0$
tMTD	Mechanothermodynamic state in time $\sigma_{ijT}, T_\Sigma, t$	$u_\Sigma^{eff} \overset{\sigma_{ijT} \to \sigma_{\lim}(T)}{\underset{\substack{T_\Sigma \to T_S \\ t \to t_{\lim}}}{\Longrightarrow}} u_0$

Here: $\sigma_{\lim}$ is the limiting stress; T_S is the melting point; $t_{\lim}$ is the longevity; σ_{ij} is the stress (strain) tensor; T_Σ is the temperature due to all heat sources; σ_{ijT} is the stress tensor in the isothermal ($T_\Sigma = \text{const}$) state; σ_{ijT}, T_Σ is the stress-strain state and the thermodynamic state, respectively; $\sigma_{ijT}, T_\Sigma, t$ is the stress-strain state and the thermodynamic state in time, respectively

Table 2.2 Concrete definition of characteristics and their physical signs of the limiting state

Criterion condition	Condition of reaching the limiting state	Physical sign
L1	$\sigma_{\lim} = \sigma_u$	Static failure
	σ_u—tensile strength limit	
L2	$\sigma_{\lim} = \sigma_{-1}$	Fatigue failure (into parts)
	σ_{-1}—mechanical fatigue limit	
L3	$\sigma_{\lim} = p_f$	Pitting cavities of critical density (critical depth), excessive wear
	p_f—rolling fatigue limit	
L4	$\sigma_{\lim} = \tau_f$	Limiting wear
	τ_f—sliding fatigue limit	
L5	$\sigma_{\lim} = \begin{cases} \sigma_{-1p} \\ \sigma_{-1\tau} \end{cases}$	Fatigue failure (into parts) depending on contact pressure (subscript p) at rolling or on friction stress (subscript τ) at sliding (direct effect in Tribo-Fatigue)
	$\sigma_{-1p}, \sigma_{-1\tau}$—stress limit during the direct effect implementation	
L6	$\sigma_{\lim} = \begin{cases} p_{f\sigma} \\ \tau_{f\sigma} \end{cases}$	Pitting cavities of critical density (critical depth) or excessive wear at rolling or sliding depending on the level of cyclic stresses σ (subscript σ) (back effect in Tribo-Fatigue)
	$p_{f\sigma}, \tau_{f\sigma}$—stress limit during the back effect implementation	
L7	$\sigma_{\lim} = \sigma_{-1q}$	Fatigue failure at fretting corrosion and (or) fretting wear
	σ_{-1q}—fretting fatigue limit	
L8	$\sigma_{\lim T} = \sigma_{-1T}$	Limiting state depending on temperature (isothermal fatigue)
	σ_{-1T}—isothermal fatigue limit	
L9	$T_{\lim} = T_S$	Thermal (thermodynamic) damage
	T_S—melting point	
L10	$t_{\lim} = t_c$	Time (physical) prior to the onset of the limiting state on the basis of any sign
	t_c—longevity	

As for the determination of the parameters $\Lambda_{M\backslash T}$ and $\Lambda_{n\backslash\tau}$, it is shown in [1, 37, 43] that, for example, the parameter $\Lambda_{n\backslash\tau}$ is the function of the *relative (with respect to the limiting state) skewness coefficient* [see (2.45)] *of wear-fatigue damage:*

$$\bar{\rho}_{n\backslash\tau} = \left(\frac{\tau_w}{\tau_f}\right)^2 \left(\frac{\sigma_{-1}}{\sigma}\right)^2. \tag{2.64}$$

Hence, it follows that $\bar{\rho}_{n\backslash\tau}$ depends not only on the absolute values of effective (σ, τ_w) and limiting (σ_{-1}, τ_f) stresses, but also on their ratios, namely: τ_w/σ, σ_{-1}/τ_f, σ_{-1}/σ, $\tau_w/\tau_f \gtrless 1$. This means, for example, that significantly different patterns of irreversible damage accumulation will be implemented depending on the realization of this or that of the inequalities $\sigma \gtrless \sigma_{-1}$, $\tau_w \gtrless \tau_f$. This conclusion corresponds to the known experimental results and theoretical models. Figure 2.12 shows the analysis with regard to the possible dependences $\log \Lambda_{n\backslash\tau} - \log\bar{\rho}_{n\backslash\tau}$ [37, 43]. A more detailed analysis of the interdependences $\Lambda_{n\backslash\tau}\left(\bar{\rho}_{n\backslash\tau}\right)$ can be found in [1, 37, 43].

The dependence of the interaction parameter $\Lambda_{T\backslash M}$ on the parameter $\bar{\rho}_{T\backslash M}$ can be analyzed in a similar way. Such a dependence of steel, aluminum alloys, and nickel (according to the extensive experimental results [1, 37, 43]) in the double logarithmic coordinates is shown in Fig. 2.13. The correlation coefficient has appeared to be very high: from $r = 0.862$ to $r = 0.999$. The dependence $\Lambda_{T\backslash M}(\bar{\rho}_{T\backslash M})$ as a rule, undergoes sudden changes for $\lg\ \bar{\rho}_{T\backslash M} = 0$, i.e., at the value $\bar{\rho}_{T\backslash M} = 1$ when thermal and force damages appear to be equilibrium (as compared to the similar changes in the plots in Fig. 2.12).

For steels and nickel, at $\bar{\rho}_{T\backslash M} < 1$ the direct dependence is found between $\Lambda_{T\backslash M}$ and $\bar{\rho}_{T\backslash M}$, and at $\bar{\rho}_{T\backslash M} > 1$ it becomes inverse. For aluminum alloys, the dependence $\Lambda_{T\backslash M}(\bar{\rho}_{T\backslash M})$ is also direct, but it is located (at $\bar{\rho}_{T\backslash M} < 1$) in III quadrant.

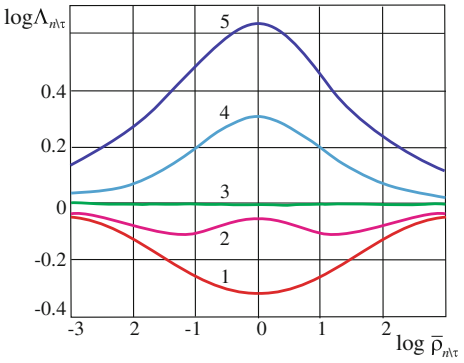


Fig. 2.12 Typical character and direction of hardening-softening processes $(\Lambda \gtrless 1)$ versus the skewness coefficient of damageability $\bar{\rho}$: *1*, *2*—mechano-rolling fatigue; *2*, *3*, *4*—mechano-sliding fatigue; *4*, *5*—fretting fatigue

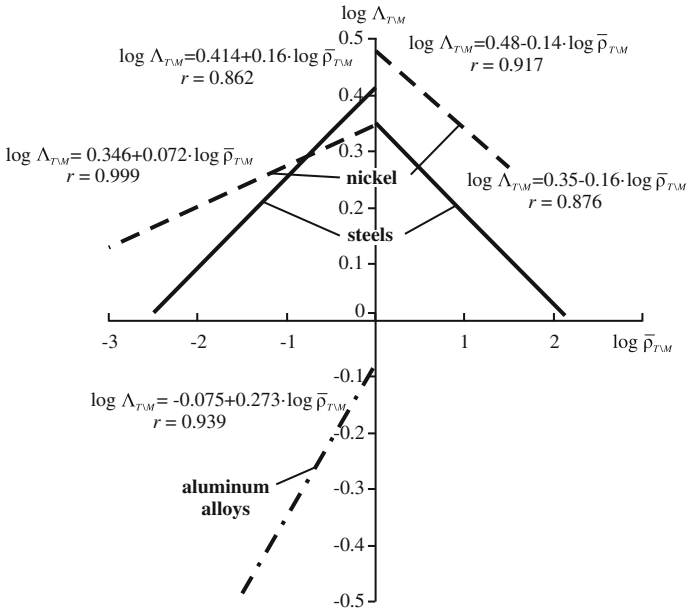


Fig. 2.13 Logarithmic dependences of $\Lambda_{T\backslash M}(\bar{\rho}_{T\backslash M})$ built using the experimental data (L.A. Sosnovskiy, A.V. Bogdanovich)

Thus, it is experimentally confirmed that *the interaction parameter* $\Lambda_{T\backslash M}$ *is sensitive not only to the effective thermal-to-mechanical energy ratio, but also to the structure and composition (or nature) of metal materials*. The last conclusion is also valid for the parameter $\Lambda_{n\backslash\tau}$: its numerical values appear to be significantly different, for example, for metal/metal and metal/polymer active systems—even in the case when the ratios $\sigma\backslash\sigma_{-1}$ and $\tau_w\backslash\tau_f$ are identical for them.

2.7 Summary of Experimental Data

The data of more than 600 tests of metals and their alloys (under isothermal conditions) obtained by many authors are briefly analyzed and have been presented above (see Sect. 2.6). It was found that the thermodynamic dependence of limiting stresses can be represented in the $\log\sigma_{\lim} - \log C_T$ coordinates (Figs. 2.3 and 2.4 and formula (2.63), where the function

$$C_T = C_T\left(T, u_0, a_n, a_T, \Lambda_{M\backslash T}\right) \tag{2.65}$$

is satisfactory under both the conditions of static tension ($\sigma_{\lim} = \sigma_u$) and fatigue failure ($\sigma_{\lim} = \sigma_{-1}$) for numerous and different metal materials (steels; aluminum,

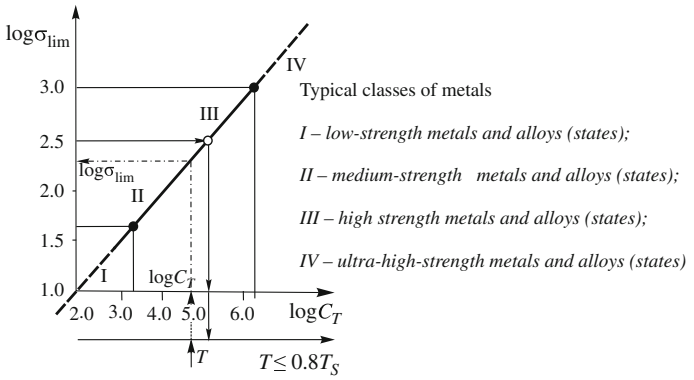


Fig. 2.14 Generalized MTD function of limiting states of metals and alloys $\sigma_{\text{lim}} \leq \sigma_u$; $T_\Sigma \leq 0.8T_S$

titanium, and other alloys, etc.). In addition, interrelation (2.63) appears to be valid practically within the entire possible ranges of temperature $(T_\Sigma \leq 0.8T_S)$ and stress $(\sigma \leq \sigma_u)$ with the correlation $r = 0.7$ in the specific cases and usually with $r > 0.9$. Model (2.63) then turns to be *fundamental* (Fig. 2.14). First, this simplified model might seem to be questionable since in the known literature [4, 42, etc.], the explicit temperature dependence of limiting stresses is described by means of complex curves. This is attributed to the changes in the mechanisms of damage of different materials under various testing conditions—at normal, operating, and other temperatures. Nevertheless the fundamental nature of model (2.63) is convincingly confirmed experimentally (Figs. 2.3 and 2.4).

From the theoretical standpoint, the following considerations speak in favor of model (2.63). It has four parameters [formula (2.65)], and one of them (u_0) is a fundamental constant of substance [formulas (2.24), (2.25)], and two others (a_T, a_n) are defined by boundary conditions (2.54) as the relations for u_0 and physical constants σ_d and T_d of a given material:

$$a_n = u_0/\sigma_d^2, a_T = u_0/T_d. \tag{2.66}$$

The methods of σ_d and T_d determination are described in [1, 37, 43]. Here we remind that the material destruction limit σ_d is determined under the tension conditions as $T_\Sigma \to 0$ and the material destruction temperature T_d—at the solid heating for $\sigma = 0$. As can be seen from the above, the *dual character of accumulation processes of damage and failure* caused by (1) mechanical stress and (2) thermal activation of this stress in time [48] is considered in the general case. Finally, as briefly described above and outlined in [18, 37], the function $\Lambda_{M\setminus T} \gtrless 1$ considers the interaction of damages due to changes in $\sigma \gtrless \sigma_{\text{lim}}$. In the known studies (see, for example [14]), it is also convincingly proved many times that just this relation is responsible for the character and damage mechanisms at elastic,

inelastic, elasto-plastic and plastic strain. Also, the role of thermal fluctuations $(T_\Sigma < T_d)$ is, for example, studied in detail in [16, 48].

It remains for us to put the "last point" in the argument in favor of the fundamental character of model (2.63). If it is really fundamental, then it must also be valid for non-metal, for example, polymer materials—according to hypothesis (2.24). The analysis results of polymer tests based on experimental data are presented in Fig. 2.15 and in Table 2.3. It is seen that model (2.63) is verified by the correlation coefficient $r = 0.917$. Note that the test results for not only "normal" samples (with a diameter of ~ 5 mm), but also for thin polymer threads and films

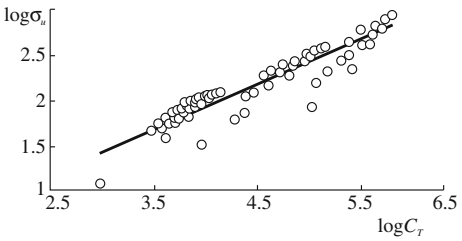


Fig. 2.15 Dependence $\sigma_u(C_T)$ for polymer materials (A.V. Bogdanovich)

Table 2.3 Main characteristics of polymer materials analyzed in terms of the energy criterion [15, 21]

Material and reference	$u_0, \frac{\text{kJ}}{\text{mol}}$	$\frac{a_T}{a_n}, \frac{\text{MPa}^2}{\text{K}}$ $\left(\frac{\text{kJ}}{\text{mol K}} / \frac{\text{kJ}}{\text{mol MPa}^2}\right)$	Test data	
			$\frac{\text{K}}{\sigma_b, \text{MPa}}$	Sample size
High-density polyethylene film (HDPF), grade 20806-024	108	$\frac{0.275}{2.94\times10^{-4}}$	$\frac{275-383}{32-386}$	5
Polypropylene film (PF), grade 03P10/005	119	$\frac{0.234}{1.70\times10^{-4}}$	$\frac{273-423}{150-570}$	5
Hardened staple fiber made of polyvinyl alcohol (PVA) "Vinol MF"	111	$\frac{0.227}{7.62\times10^{-5}}$	$\frac{273-453}{80-802}$	5
Thread based on perchlorvinyl resin (PCV), grade "Chlorine"	114	$\frac{0.285}{2.56\times10^{-4}}$	$\frac{273-383}{60-376}$	5
Caprone thread, (GOST 7054067)	169	$\frac{0.282}{1.68\times10^{-4}}$	$\frac{275-453}{300-740}$	5
Polyethylene terephthalate film (PET), (TU 6-05-1597-72)	222	$\frac{0.342}{9.82\times10^{-4}}$	$\frac{279-498}{200-362}$	4
Polyamide film PM-1, (TU 6-05-1597-72)	202	$\frac{0.297}{2.1\times10^{-3}}$	$\frac{273-673}{12-240}$	7
Polystyrol (PS) at bending	281	$\frac{0.627}{2\times10^{-2}}$	$\frac{77-290}{56-108}$	10
Polymetalmethacrylate (PMMA) at bending	277	$\frac{0.558}{1.74\times10^{-2}}$	$\frac{77-290}{66-116}$	10
High-impact polystyrene (HIPS) at tension and torsion	277	$\frac{0.699}{2.53\times10^{-2}}$	$\frac{77-290}{48-94}$	10
	252	$\frac{0.636}{1.84\times10^{-2}}$	$\frac{77-290}{50-105}$	10

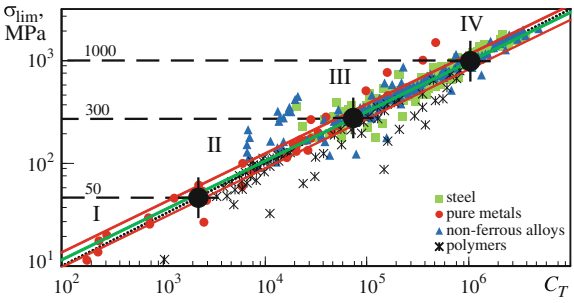


Fig. 2.16 Experimentally justified MTD function of states critical with respect to damageability for pure metals, non-ferrous alloys, structural steel and polymer materials

are processed not only at tension, but also at torsion and bending. A large deviation of several points from the fundamental straight line is due to the fact that for these results $\Lambda_{M\setminus T} = 1$ is conventionally assumed thanks to the lack of experimental data in effort to assess the real value of this parameter.

The *generalized experimentally justified MTD function of the limiting states (*in terms of *damageability)* is shown in Fig. 2.16. Relatively large deviations of particular experimental points from the predicted ones are also seen in Figs. 2.3 and 2.4 for two reasons: either available references lack sufficient data for a correct assessment of required parameters, or the conducted experiments contain significant errors or they are not quite correct methodically. A possible analysis of other researchers will show this was true or not.

Note that model (2.63) may seem to be non-fundamental because of its simplicity. However, remind the saying that has become a classic dictum: the fundamental dependence cannot be complicated (or: any law is described by the simplest formula. Thus, model (2.63) can serve for prediction (shown by the arrows from T to $\sigma_{\lim}$ in Fig. 2.14) of the *mechanical behavior of materials in the thermodynamic medium*:

$$T \xrightarrow[\uparrow \overline{a_n, a_T}]{\overset{u_0, \Lambda_{M\setminus T}}{\downarrow}} \lg C_T \rightarrow \lg \sigma_{\lim}\left(T, u_0, a_n, a_T, \Lambda_{M\setminus T}\right) \rightarrow \sigma_{\lim(T)}. \tag{2.67}$$

The state of the medium in (2.67) is described with the use of the parameters T, a_T and $\Lambda_{M\setminus T}$.

As seen, the predictions by (2.63) and (2.67) are applicable for the materials of different nature and structure—irrespective of damage and failure mechanisms at static and cyclic loads. It would be interesting to make a similar analysis of the tests at impact, but such an analysis lies outside the scope of the present work.

Certainly, due to the linearity of function (2.63), the *reverse prediction* appears to be possible and effective. If it is necessary to have a given mechanical state of material (determined by u_0, $\sigma_{\lim(T)}$), then the requirements can be formulated to the

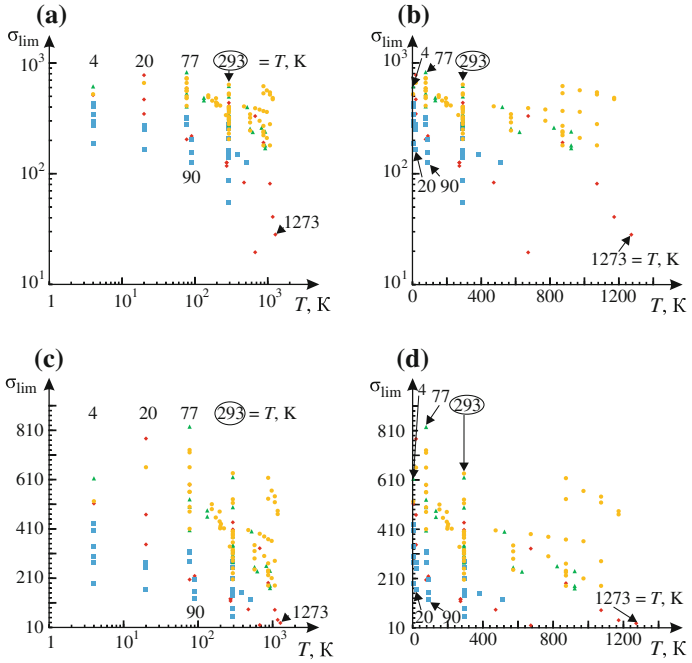


Fig. 2.17 (Beginning) Explicit temperature dependences of the fatigue limit for structural steels in logarithmic **a**, semi-logarithmic **b**, **c** and uniform **d** coordinates

medium (determined by the parameters T, a_T, $\Lambda_{M\setminus T}$) in which the system can operate (shown by the arrows from $\sigma_{\lim}$ to T in Fig. 2.14):

$$\sigma_{\lim(\mathrm{T})} \rightarrow \lg \sigma_{\lim(\mathrm{T})} \xrightarrow[\uparrow\ a_n,\ a_T]{\downarrow\ u_0,\ \Lambda_{M\setminus T}} \lg C_T \rightarrow C_T\left(T, u_0, a_n, a_\tau, \Lambda_{M\setminus T}\right) \rightarrow T. \quad (2.68)$$

Note that the attempts to construct the explicit temperature dependence of limiting stresses in uniform, semi-logarithmic and logarithmic coordinates for different materials and various test conditions are quite ineffective because a relatively small amount (136) of test results, as shown in Fig. 2.17.

Further, we briefly analyze a more complex *problem of the MTD system operation in the medium* in which the processes of *thermal corrosion and stress corrosion* are implemented. From (2.52), at $\tau_w = 0$ we have

$$\Lambda_{M\setminus T}\left(\frac{a_T}{1-D_T}T_\Sigma + \frac{a_n}{1-D_n}\sigma^2\right) = u_0. \quad (2.69)$$

Upon simple manipulations, we obtain

$$\sigma_{\lim(T,ch)} = \frac{1}{2}\lg C_{T(ch)} \tag{2.70}$$

where, as can be easily shown, the parameter of resistance to thermal stress corrosion is:

$$C_{T(ch)} = C_{T(ch)}\left(T, u_0, a_n, a_T, \Lambda_{M\setminus T}, v_{ch}, v_{ch(\sigma)}, m_{v(\sigma)}, v_{ch(T)}, m_{v(T)}\right). \tag{2.71}$$

It can be seen that laws (2.63) and (2.70) are fundamentally (and formally) identical and differ in the fact that appropriate functions (2.65) and (2.71) take account of those parameters which describe the damageability processes characteristic for the phenomena analyzed. So, in (2.71) the parameters $v_{ch}, v_{ch(\sigma)}, m_{v(\sigma)}, v_{ch(T)}, m_{v(T)}$ describe the processes of thermal stress corrosion. Based on (2.70) and (2.71), it is easy to build *prediction algorithms* [of form (2.67) and (2.68)] *of resistance to thermal stress corrosion*.

A further and detailed analysis of (2.70) and (2.71) is beyond the scope of this study.

Note that solutions (2.52)–(2.62) can be analyzed similarly for other testing (or operating) conditions.

Thus, a single MTD function of critical with respect to damageability states of metals and polymers working in various conditions has been obtained above. The analysis of more than 600 experimental results (Figs. 2.3, 2.4, 2.13, 2.15 and 2.16) showed that this function is fundamental: it is valid for low-, mean- and high-strength states of pure metals, alloys, and polymers over a wide range of medium temperatures (from helium to $0.8T_S$, where T_S is the melting point of material) and mechanical loads (up to the strength limit for single static loading); the fatigue life was of the order of 10^6–10^8 cycles.

The fundamental MTD function as found in the present study can be used for effective prediction of the behavior of particular MTD systems in various operating (test) conditions. Model (2.70), (2.71) is proposed for the description of the influence of thermal corrosion and stress corrosion on the changes in the limiting states of materials.

2.8 Translimiting States

According to the available information, the *theory of translimiting states* is not yet sufficiently developed [37]. The elements of this theory will be set forth on the basis of solutions (2.47), (2.51) and (2.52).

Figure 2.18 shows the general analysis of the contribution of *mechano-chemico-thermal damage* (parameters D) to the process of reaching the limiting state by the

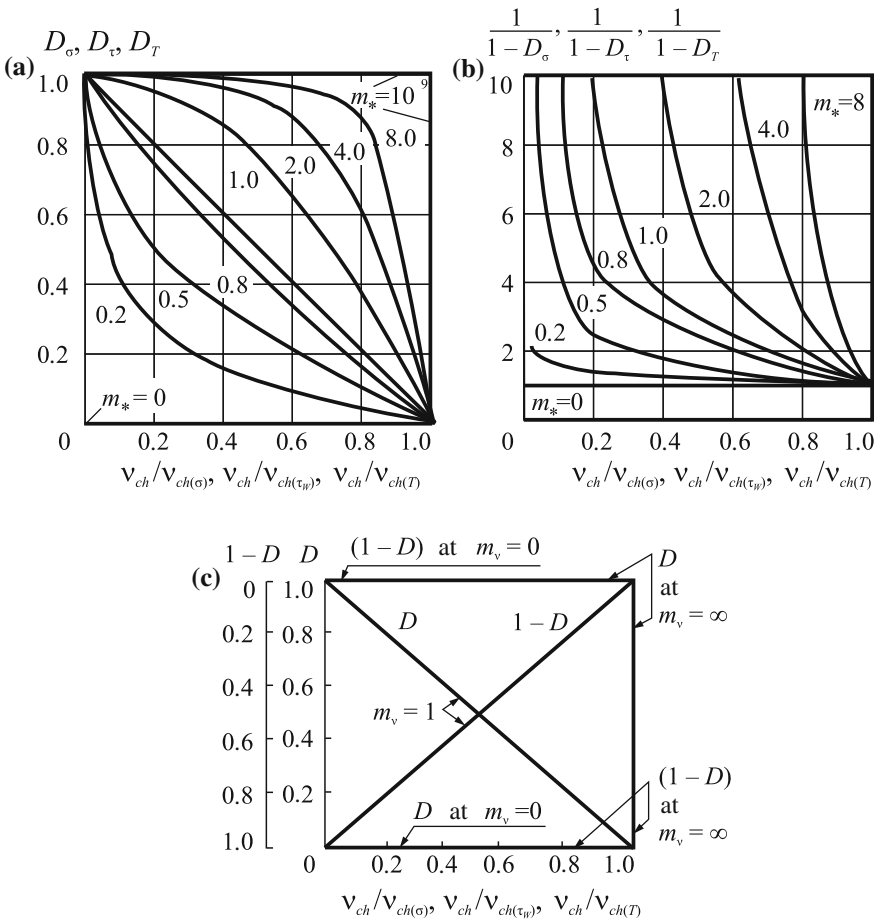


Fig. 2.18 Analysis of the influence of mechano-chemico-thermal processes on the system damageability

MTD system. Based on the analysis of formulas (2.47)–(2.52) and Fig. 2.18, the following conclusions can be drawn.

1. The growth of parameters D means a decrease in a relative damage rate $v_{ch}/v_{ch(*)}$ (Fig. 2.18a). In other words, mechano-chemico-thermal damage accelerates the achievement of the limiting state by the MTD system the faster, the greater is the value of the parameter D and/or of the rate $v_{ch(*)}$.
2. The parameter m_ν exerts the strongest influence on the system damage, and it is the stronger, the larger is its value (Fig. 2.18b). The important feature of this influence is that this environment is very sensitive to the excitation of mechanical stresses in the MTD system and to the temperature rise if for it the parameter $m_\nu > 5$. In other words, in such a case, the translimiting state can be realized, for which damageability measure (2.29) is more than unity ($\psi_u^{eff} > 1$),

whereas according to (2.28), it is sufficient to have $\psi_u^{eff} = 1$ to reach the limiting state

Two specific cases are illustrated in Fig. 2.18c.

(1) $D = 0$. There is no electrochemical corrosion influence on wear-fatigue damage. But this doesn't mean that the electrochemical corrosion process does not occur. In fact, according to (2.51), when $D = 0$, we have (if $m_v = 1$):

$$1 - \frac{v_{ch}}{v_{ch(*)}} b_* = 0.$$

This implies that the situation should be the following: $b_* = 1$ and $v_{ch} / v_{ch(*)} = 1$, i.e., the corrosion rate is insensitive to this factor (mechanical or frictional stress). This means that *threshold values* of σ^0, τ_w^0, and T^0 exist for a given environment. The corrosion rate in such an environment does not vary for $\sigma \le \sigma^0$, $\tau_w \le \tau_w^0$ and for $T_\Sigma \le T^0$ [formula (2.52)].

(2) $D = 1$ and, hence, $1/(1 - D) \to \infty$. Explosive damage is realized within the system as $\psi_u^{eff} \to \infty$. In this case, it should be

$$\frac{v_{ch}}{v_{ch(*)}} b_* = 0.$$

Since $v_{ch} = 0$ is impossible, it can be assumed that $v_{ch(*)} \to \infty$. This is just the *condition of mechano-chemico-thermal explosion* in the MTD system. The explosion is not just due to the environmental influence—the environmental influence dramatically enhanced by temperatures and mechanical stresses.

Thus, complex function (2.47) for the damageability of MTD systems can also be used for *analyzing their translimiting states* caused by a supercritical growth of thermodynamic, mechanical, frictional, and electrochemical loads according to formulas (2.48)–(2.51), i.e.,

$$1 \le \psi_u^{eff} = \Lambda_{T\backslash M}\left[\psi_{T(ch)} + \Lambda_{n\backslash\tau}(\psi_{n(ch)} + \psi_{\tau(ch)})\right] \le \infty. \tag{2.72}$$

According to (2.72), there are *many translimiting states* of the MTD system defined by the condition $\psi_u^{eff} > 1$. This is possible in those (many) cases when the critical with respect to damageability state of the system is reached not at one but at many points of the dangerous volume. Hence the assumption can be made that *many (different) forms* of these states must exist. As an example, some forms of translimiting states of a real wheel/rail system observed in operating and testing conditions [36, 37] are presented in Figs. 2.19 and 2.20.

In [22], it is possible to find the form of function (2.72) and its analysis for the simplest Tribo-Fatigue system (shaft/sliding bearing).

Although above-mentioned criterion Eqs. (2.19), (2.23), (2.28), (2.33), (2.47), (2.52) are obtained from the consideration of the energy conditions of reaching the limiting state, it is stated that they can in principle be used for describing a variety

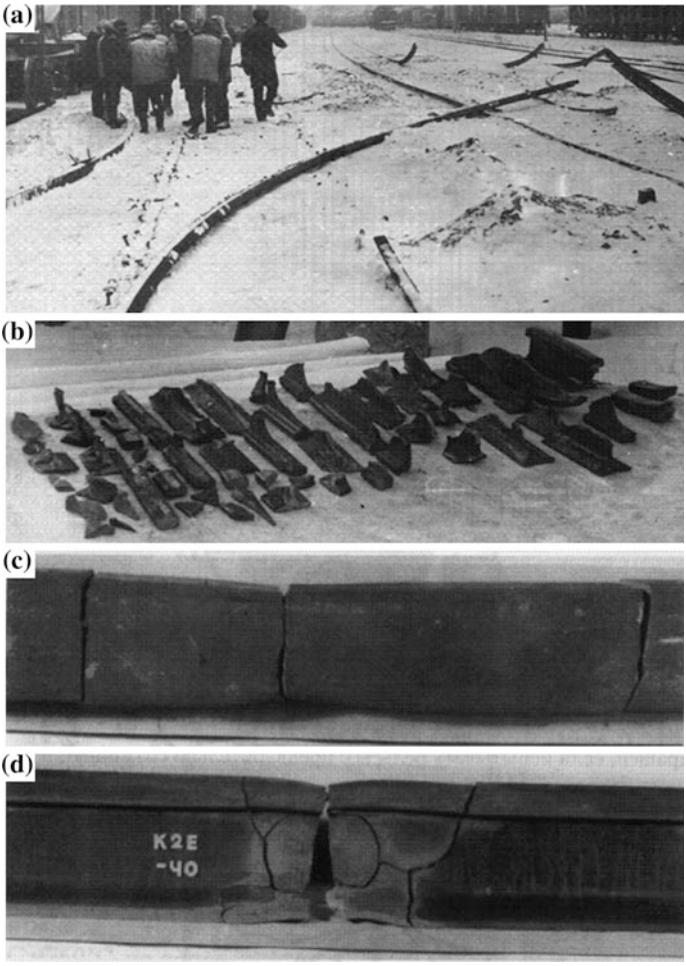


Fig. 2.19 Four forms of the translimiting state of rails appeared in the operation **a**, **b** (V.I. Matvetsov), and detected in the three-point bending tests **c**, **d** (M.N. Georgiev et al.)

of translimiting states, but only in those cases when situations in the MTD system are created for an *unconditional supercritical* (essentially *unrestrained*) growth of loads (explosions, accidents, disasters, fires, etc.).

Another more general approach for the analysis of translimiting states is that it considers a *damage space* defined according to (2.34), (2.39) by volumetric measures

$$0 \leq \omega_{ij} = \frac{V_{ij}}{V_0} \leq 1. \tag{2.73}$$

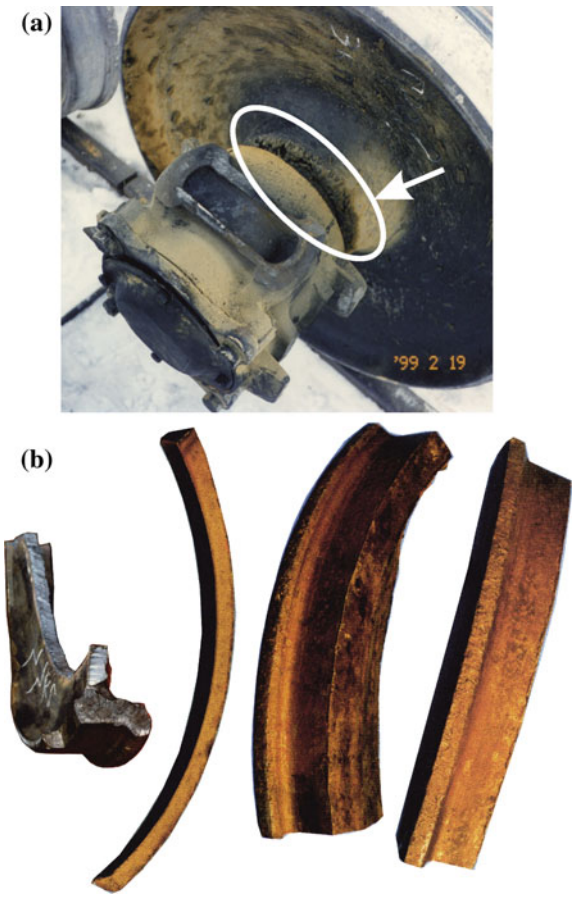


Fig. 2.20 Two forms **a**, **b** of the translimiting state of the freight car wheel appeared in the operation (I.F. Pastukhov)

On the basis of (2.47)–(2.51), spatial measures of damageability can be defined as

$$\omega_{n(ch)} = \frac{V_{P_\gamma}}{V_0(1-D_n)},\ \omega_{\tau(ch)} = \frac{S_{P_\gamma}}{S_0(1-D_\tau)},\ \omega_{T(ch)} = \frac{V_{T_\gamma}}{V_0(1-D_T)}, \tag{2.74}$$

where V_0, S_k are the working volume and the surface, respectively. So criterion (2.33) can be written with regard to (2.74):

$$\Lambda_{T\backslash M}\left[\frac{V_{T_\gamma}}{V_0(1-D_T)} + \Lambda_{n\backslash\tau}\left(\frac{V_{P_\gamma}}{V_0(1-D_n)} + \frac{S_{P_\gamma}}{S_0(1-D_\tau)}\right)\right] = 1. \tag{2.75}$$

The advantage of (2.75) is that the interaction of dangerous volumes [37] at different loads is taken into account when the limiting state of MTD systems is formed. In addition, as mentioned above, since absolute dangerous volumes are determined by a number of structural-technological and metallurgical factors (2.39),

these factors appear to be automatically accounted for in the limiting state criterion for such systems.

If the rupture of atomic bonds is realized only over one dangerous section of an object at all "points" of this section ($u_{\Sigma}^{eff} = u_0$), then it is divided into two parts, which corresponds to the condition $\omega_{\Sigma} = 1$. But if the complex of loads (mechanical, electrochemical, thermodynamic, etc.) is such that the rupture of "all" atomic bonds takes place over this section, then the process occurs and it is called *disintegration of an object,* whose death corresponds to the condition $\omega_{\Sigma}^{*} = \infty$. This is the most *common form of the translimiting state*: the system disintegrates into an infinite number of particles of arbitrarily small size (for example, atoms). It is clear that there must be some *intermediate forms of the translimiting states of the system.* The condition of their implementation is

$$1 \le \omega_{\Sigma}^{*} = \Lambda_{T\backslash M}\left[\left(\omega_{n(ch)} + \omega_{\tau(ch)}\right)\Lambda_{\sigma\backslash\tau} + \omega_{T(ch)}\right] \le \infty. \tag{2.76}$$

Naturally, Eq. (2.76) is similar to (2.72). Their difference is that conditions (2.72) are written in terms of energy measures of damage, while conditions (2.76)—in terms of volumetric (spatial) measures of damage.

The general *classification* of conceivable *states of an object* in terms of *volumetric damage* is given in Table 2.4 that is similar to the one in Table 2.1 [25], but with the difference that a special index (asterisk*) is introduced for translimiting states.

The probability interpretation [33, 44] of irreversible damage events in the MTD system can be made according to Table 2.4 and condition (2.76).

If

$$0 \le P(\omega_{\Sigma}) \le 1 \tag{2.77}$$

is the *classical probability of the MTD system failure* in terms of *damageability* $(0 \le \psi_{\Sigma} \le 1)$ within the time interval $(t_0, T_{\oplus})$ (Item XIV), then $P(\omega_{\Sigma} = \omega_c = 1) = 1$ is the *reliable probability of unconditional functional failure*. For transmitting states the *concept of reliable probability* [33] is introduced

$$1 \le P_{*}\left(\omega_{\Sigma}^{*}\right) \le \infty. \tag{2.78}$$

Table 2.4 Characteristic of the states of objects

A-state	Undamaged	$\omega_{\Sigma} = 0 = \omega_0$	*A*-evolution: characteristic system states in terms of damageability
B-state	Damaged	$0 < \omega_{\Sigma} < 1$	
C-state	Critical (limiting)	$\omega_{\Sigma} = 1 = \omega_c$	
D-state	Supercritical (translimiting)	$1 < \omega_{\Sigma}^{*} < \infty$	
E-state	Disintegration	$\omega_{\Sigma}^{*} = \infty = \omega_{\infty}^{*}$	

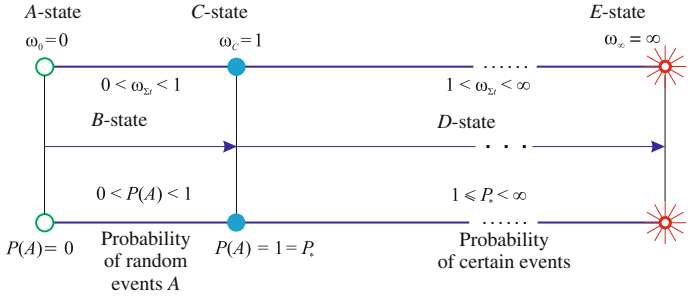


Fig. 2.21 Relationship between the system damages and the probability

These *supercritical damages* $1 < \omega_\Sigma^* < \infty$ correspond to numerous and infinite shapes and sizes of fragments or particles to be formed in the process of degradation (disintegration) of the system.

Figure 2.21 illustrates the relationship between the system damages and the probability.

Note that the data in Table 2.4 can be interpreted in the following way. If similar to (2.7) the damageability is

$$\omega_\Sigma^* \to \infty, \tag{2.79}$$

then the absolute size of forming particles should be as small as desired according to (2.8), i.e.,

$$d_\omega^* \to 0. \tag{2.80}$$

Assume the logarithmic relationship between d_ω and ω_Σ to a first approximation. The law of degradation

$$d_\omega^* = e^{-\omega_\Sigma^*} \text{ or } \omega_\Sigma^* = -\ln d_\omega^*. \tag{2.81}$$

As follows from the above-mentioned, all states of the MTD system are predicted by appropriate Eq. (2.72) and/or (2.76). A drawback of this prediction or the description is that the dependence of damageability measures [for example, (2.72)] on the determining parameters appears to be smooth over the entire range $0 \leq \omega_\Sigma \leq \infty$ (Fig. 2.22a). It should be noted, however that this is valid only in the case (essentially, in the ideal case) when the values of the determining parameters (σ, τ_w, Λ, etc.) are continuously increasing. But the *surface of damageability reveals jumps* (*discontinuities*) whenever either discontinuities of any load or abrupt changes in hardening-softening processes (Fig. 2.22b, c) are realized. It is easy to understand that in reality, these specific situations lead to *damageability discontinuities*, i.e., to *qualitative changes* or *system state transformations*. It should be added that our approach has a special advantage: it is based on the analysis of *damageability as a physical reality* independent of the fact what damage mechanisms are already known to us and what mechanisms will be clarified.

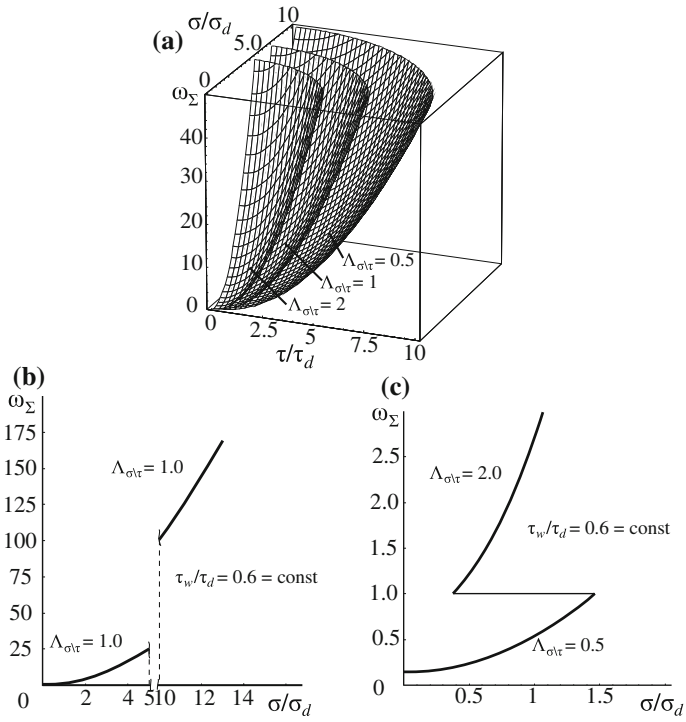


Fig. 2.22 Formation of damageability surfaces **a** and functions **b**, **c** ω_Σ due to the changes in the determining parameters ($\sigma / \sigma_d > 0$, $\tau / \tau_d > 0$, $\Lambda_{\sigma\backslash\tau} > 0$)

The last comment is of particular importance. The fact is that when the "*conventional failure of a regular mechanical object*" ($\omega_\Sigma = 1$) occurs, i.e., it disintegrates, at least, into two parts, the existence of the MTD system does not end—in accordance with Item XIV, a long period comes when an object disintegrates into particles $(1 < \omega_\Sigma^* \leq \infty)$. Here, not so much mechanical loads, as electrochemical and thermodynamic phenomena (processes) are the determining parameters. On the basis of the above-said, the *law of any disintegration* (*decomposition*) *of the MTD system* is formulated in the form

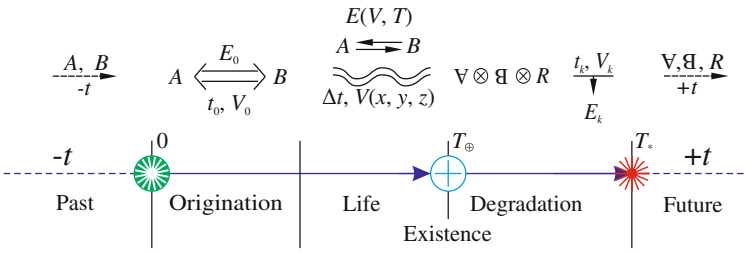
$$\sum m_{V_{ijT}} = m_{V_0}. \tag{2.82}$$

Law (2.82) suggests the mass conservation of the system regardless of the conditions of its degradation and disintegration. In other words, the *mass of disintegrating particles* $\sum m_{V_{ijT}}$ (whatever their size) *cannot exceed* (or it can be less than) the *initial mass* m_{V_0} of *the MTD system*.

Hence, there is the need of the analysis (at least, short) of the *evolution of systems*.

2.9 Evolution of a System by Damageability

Give the description according to Tribo-Fatigue [39] of the behavior of the *deformable solid-solid system* in some environment on the most general—dialectical grounds. The *origination* of the system, *existence* (*occurrence, life* and *degradation*) can be represented in the following general form:



(2.83)

Here *A, B* are some separate bodies (elements, etc.), details, objects. Their existence in the past ($-t$) is sketched by the dashed line with an arrow.

This writing

$$A \overset{E_0}{\underset{t_0, V_0}{\Leftrightarrow}} B \tag{2.84}$$

means that the *creation (origination) of a system (or an object)* is the product of energy (E_0) interaction ($\leftrightarrow$) of bodies *A, B* implemented in the time t_0 within the volume V_0. Of course, this product is neither *A* nor *B*; but it is an entity with special integral characteristics and functions which neither *A* nor *B* can possess.

The writing

$$\begin{matrix} E(V, T) \\ A \rightleftharpoons B \\ \sim \\ \Delta t, V(x, y, z) \end{matrix} \tag{2.85}$$

means that the *life of the system* is the process of its energy $E\,(V, t)$ interaction with the environment $V\,(x, y, z)$ during the time Δt. This interaction with the environment always causes surface damages to originate and accumulate in the system elements since *t, V, E* are variable. The system itself is also characteristic for the force interaction of its elements ($A \leftrightarrows B$). This means is that not only surface damage, but also volumetric (internal) damage should arise and develop, since the forces of such interaction are distributed over the volume of the elements and vary with time. Therefore the life (longevity) of the system is shown in (2.83) and (2.85) by the wavy lines. *Accumulation of irreversible surface and volumetric damages is the softening process which eventually causes the system degradation and death.*

Assume that the *system elements,* as well as the *entire system reveal the hardening property*, i.e., the ability to increase its resistance by both external and internal influences when they are hardened. Then *the outcome* of *struggle of opposites* (i.e., *hardening-softening processes*) also *determines the life of the system, or its existence time (operation)*. If the damageability level grows in time, then the system degrades inevitably, as soon as the damageability reaches some limiting (or critical) value.

Thus the writing

$$\forall \otimes \mathfrak{B} \otimes R \quad \overset{t_k,\, V_k}{\underset{E_k}{\blacktriangledown}} \tag{2.86}$$

means the following. The *degradation of the system* is the process that leads to its disintegration within the volume V_k in the time t_k into fragments ($\forall$, $\mathfrak{g}$) and residues R. The degradation is accompanied by the release of the energy E_k; the fragments and residues dispersed in time and space constitute a set ($\otimes$) of disintegration products.

The *products of system degradation* are represented by three components in expressions (2.83) and (2.86). First, these are the modified bodies A and B (denoted as $\forall$ and $\mathfrak{g}$, respectively). Secondly, these are system residues (denoted as R). In other words, $\forall$ and $\mathfrak{g}$) are the recognizable parts (fragments) of the disintegration products of the system since A and B are their images. As far as R is bodies designated as $\forall$ and $\mathfrak{g}$). Second, these are the residuals of the system designated as R. In other words, $\forall$ and $\mathfrak{g}$) are recognizable parts of disintegration products since A and B are their images. As for R, it is the unrecognizable (or hardly recognizable) part of the disintegration products of the system. This part can be represented as the one consisting of at least four components:

$$R = R\,(R_A^{\mathfrak{g}},\, R_B^{\forall},\, R_{A,\forall}^{t,V},\, R_{B,\mathfrak{g}}^{t,V}), \tag{2.87}$$

i.e., the $R_A^{\mathfrak{g}}$'s are the residuals A embedded in $\mathfrak{g}$ and trapped by it. The $R_B^{\forall}$'s are the residuals B in $\forall$, i.e., these are the fragments B embedded in $\forall$ and trapped by it. The $R_{A,\forall}^{t,V}$'s are the residuals A and $\forall$ dissipated in the space (environment) V and in the time t. Finally, the $R_{B,\mathfrak{g}}^{t,V}$'s are the residuals B and $\mathfrak{g}$ dissipated in the space V and in the time t.

Residuals and fragments are going in the future ($+t$). Their existence is shown in (2.83) by the dashed arrow. This existence can be separate and is marked by the commas between the symbols $\forall$, $\mathfrak{g}$, R.

Expression (2.83) should be understood as the conventional (symbolic) writing of the sequence of interrelated processes of system origination, existence, and degradation.

As the simplest specific example, consider one of the widespread active systems: *crankshaft journal* (*A*)—*sliding bearing* (*B*) *of the rod head of the engine*. Of interest is the life of the system.

The technological process of manufacturing parts A and B ends in the assembly $A \Leftrightarrow B$—it is the process of system origination (2.84). Obviously, it is implemented in the time t_0 within the volume V_0 at the energy expenditure E_0. Then system life (2.85) begins: aging, normal operation, gradual loss of efficiency. In the course of life the system $A \Leftrightarrow B$ changes into $A \leftrightarrows B$), i.e., assembly components undergo wearing at the contact pressure q and wear-fatigue damages accumulate in the crankshaft journal when acted upon by cyclic stresses σ. This occurs when the energy E (V, t) interacts with the environment (oxidation of friction surfaces) during the entire existence time Δt. Thus, both the environment $V(x, y, z)$ and the interaction energy E vary with time. The damage accumulation causes the system to degrade according to (2.86) and, hence, its failure (wear-fatigue fracture of the crankshaft journal, frictional fracture of bearing inserts). The system undergoes failure in the environment V_k in the time t_k followed by the release of the energy E_k. In the process of failure (2.86), the fragments V and g are the parts of the shaft A and the inserts B. Also, the residuals R—wear products (2.87)—are formed: the crankshaft particles embedded into the sliding bearing inserts (R_A^g); the insert particles embedded into the crankshaft journal surface (R_B^V); the products of surface damage of the crankshaft journal ($R_{A\bar{V}}^{t,V}$) and the inserts ($R_{B,\bar{g}}^{t,V}$) scattered in the environment in the time t, i.e., the wear products removed from the friction zone.

As seen, based on (2.83), a sufficiently general and correct qualitative analysis of interactions of the system elements and the system with the environment is given.

The outlined qualitative picture can serve as a basis, for instance, for setting and describing quantitatively the life N (resource) of the active system. It is obvious that $\Delta t = N$ is the function of cyclic stresses σ in the crankshaft journal, the contact pressure q in the tribo-coupling, the wear rate I of system elements, the accumulation rate of wear-fatigue damage ϑ, the properties (composition, structure) of the environment C_V and the elements A, B of the system (C_A, C_B):

$$N = N(\sigma, q, I_\sigma, \vartheta, C_V, C_A, C_B, \ldots).$$

This equation for longevity can be specifically implemented, for instance, using the methods of applied mechanics.

Similarly, the processes of origination, life, and degradation of other systems, for example, *solid–fluid,* etc. can be described. Differences will be only in specifying what interaction forces are implemented in the investigated case and what damages arise and develop.

If *the biological system*, for example, cardiovascular or musculoskeletal is considered, then a sufficient qualitative description of its life, damage, and degradation can be made with the use of symbolic model (2.83) developed as applied to inorganic active systems. Further, it is necessary to take into account *a specific complex of biological phenomena and factors* [39]. It is shown that approach (2.83) can also be used to describe the general processes of birth, life, and death of *a living organism* that together with environment and habitat conditions forms the most complex living system in it. For this case, *the concept of Tribo-Fatigue life as a special method of damage accumulation* [36] is developed.

Table 2.5 Characteristics of damageability evolution of the MTD system

MTD system states		Parameters		State properties (physical)	State symbols	Energy conditions of states	Technogenic situations and possible damages
Symbol	Characteristic	Damageability	Integrity ($\delta = 1-\psi$)				
1	2	3	4	5	6	7	8
A	Undamaged	$\omega_A = 0$	$\delta_A = 1$	Maintaining the integrity (size, shape, mass), structures (skeleton) and support (implementation) of all functions	$V_0 = \text{const} \overset{A_0}{\underset{B_0}{\Leftrightarrow}} u_\Sigma^{eff} = 0$	$u^{eff} = 0$ $\psi_u^{eff} = 0$	Failures (e.g., short-time reversible change of function)
B	Damaged	$0 < \omega_B < 1$	$1 > \delta_B > 0$	Development of complex damageability and malfunctioning	$V_{ij} > 0 \overset{A}{\underset{B}{\rightleftarrows}} u_\Sigma^{eff} > 0$	$u_\Sigma^{eff} < u_0$ $\psi_u^{eff} < 1$	Incidents (e.g., permissible system wear)
C	Critical (limiting)	$\omega_\Sigma = 1 = \omega_C$	$\delta_C = 0$	Total functional loss, multicriterion limiting state	$C \in (V \otimes \mathcal{I})$	$u_\Sigma^{eff} = u_0$ $\psi_u^{eff} = 1 = \psi_C$ $d_c = 1$	Accidents (e.g., fatigue failure of engine shaft)
D	Supercritical	$1 < \omega_D^* < \infty$	$\delta_D < 0$	Formation of multiple fragments, dissipated fragments and residuals	$R_A^g, R_B^V, R_{AV}^{t,V}, R_{B,g}^{t,V}$	$1 > d_D^* > d$	Catastrophes (e.g., mid-air collision)
E	Disintegration (breakdown)	$\omega_E^* \to \infty$	$\delta_E \to -\infty$	Formation of nanoclusters, scattered atoms, elementary particles	✶	$d_E^* \to d_{th}$	Cataclysms (e.g., nuclear explosion)

Approach (2.83) is also used for description of the evolution of the MTD system, including in the translimiting state. Table 2.5 contains this approach with regard to the above-described diverse characteristics of system damage. It is obvious that the qualitative representation (2.83) of the evolution is supplemented here with the specific numerical analysis—at all nodal points of development (states *A, B, C*) and degradation (states *C*, *D, E*).

The general classification of the conceivable states of a system (object) in terms of damage is contained in columns 1, 2, 3. It is similar to Table 2.4, but with the specification (as marked above) that the level of critical damageability (ω_{Σ}^{*}) is assigned the superscript that means such a state. Table 2.5 also contains the appropriate physical characteristics of system states (column 5) and the additional analysis (column 4) based on the characteristic of its integrity $(\delta = 1 - \omega_{\Sigma})$. Column 6 contains the symbolic description of all system states. The above-described energy states of the system are based on conditions (2.7), (2.8) contain two uncertainties. These uncertainties are interpreted as follows. When $\psi_{D}^{*} \to \infty$ (according to condition (2.7), the absolute average size (d_{ψ}^{*}) of particles forming during the system decomposition must become arbitrarily small $(d_{D}^{*} \to 0)$ by condition (2.8). Table 2.5 reveals these uncertainties (column 7). Namely, it is assumed that transmitting states are described by the changes in the size of particles forming within the range

$$1 > d_{D}^{*} > (1/k),$$

where the left constrain is defined by unity (as a symbol of "*integrity*") and the right one—by the arbitrarily (or infinitely) *large integer k* such as within the limit

$$\lim_{k \to \text{⫛}} (1/k) = \min d_{D}^{*} = d_{\text{⫛}} \approx 10^{-k} , \tag{2.88}$$

where the *conventional, yet finite* quantity *big* (⫛) is introduced as the limit of a possible growth of the integer k to the quantity $(k = \text{⫛})$ that can be specified as the total quantity of atoms in the system under investigation. In principle, it can be calculated if the size $d_{\text{⫛}}$ of atoms is known for materials, of which the system is "made"; thus $d_{\text{⫛}} \approx 10^{-k}$. In (2.88) it is then considered that the *system death means its disintegration into such a "quantity" of particles that is equal to the initial number of atoms available in the system*. The latter can be reasonably calculated practically for any systems. It has been established, for example, that the amount of atoms in the Universe approximately equals 10^{67} [10].

Thus, the growth of the *level of translimiting damageability* of a solid $\omega_{\Sigma}^{*}, \psi_{u}^{*} > 1, d^{*} < 1$ (column 7, Table 2.5) signifies an appropriate decrease in the characteristic size of forming particles. Thus, the "location" of these particles is not specified—it can be any. But, naturally, it is meant that all particles will be finally spent for construction of those or other new systems (i.e., not necessarily—one system) [37]. This means that the *reproduction of systems* is inevitably

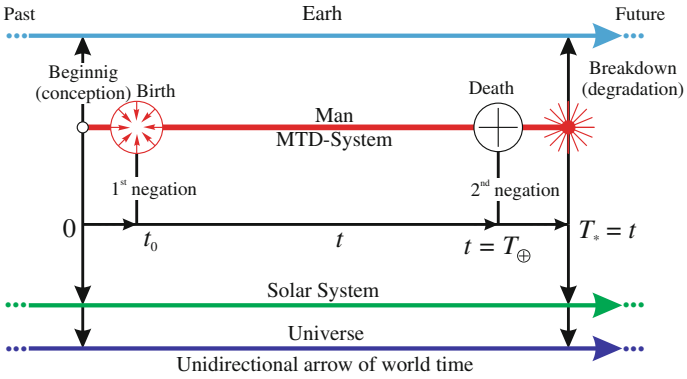


Fig. 2.23 Existence time of the material system

implemented *after their degradation*—but, of course, in new conditions with new initial parameters.

Note: a significant drawback of the performed analysis is the absence of the determining parameter—the time t.

As applied to the specific MTD system, Fig. 2.23 explains our idea of its existence. The general concept of the *unidirectional time arrow* is borrowed from thermodynamics (mostly from physics). Thus, the question about the *nature of time* is not being discussed here (as in physics and philosophy). Further, according to Item XIV, it is assumed that the *existence time of the system under examination is always finite* and is defined by the interval $(0, T_*)$ where T_* is the time before the system disintegration (Table 2.4). Within this interval the time *of its disintegration (failure)* $t = T_\oplus, T_\oplus \ll T_*$ is really defined. The failure of the system is interpreted as usual: it means the total loss of system functions and properties, which corresponds to the fact that the damageability measure (for example, ω_Σ or ψ_Σ) reaches the limiting (critical) value $\omega_c = 1 = \psi$. At the moment of failure the system, therefore, ceases to exist as a whole. Figure 2.23 shows that the existence of the system under study corresponds to a certain time interval on its any more general scale—for the Earth, the Solar system, the Universe (it is marked by the vertical arrows which separate the *past* and the *future*).

Now, describe the evolution of the MTD system.

Figure 2.24 illustrates that based on the mechanothermodynamic viewpoint, the A-evolution in time (Table 2.4) is implemented in *two stages.* The stage *ABC* $(\omega_\Sigma = \psi_u^{eff} \to 1)$ is the the *existence time of the system as* the *integrity* when it performs all its functions. It is represented as the *development accompanied by an inevitable growth of damage and deterioration of some functions* up to the moment when the limiting (critical) state is reached at the point *S*. *At this point the system completely "loses" all its functions*, for example, the accident (either the disintegration of one of the system elements into two parts, or the unacceptable (limiting) wear in system, etc.). *The second stage CDE then occurs and is represented as the*

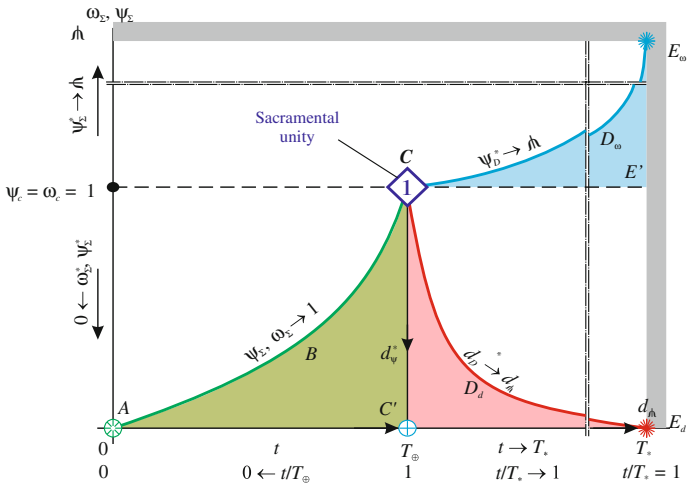


Fig. 2.24 MTD system evolution hypothesis

degradation process accompanied by the occurrence of numerous and various translimiting states caused, for example, by catastrophes, explosions, cataclysms, etc. Example: at the point *C* the vessel under static pressure is divided into 2 parts; it disintegrates into a large number of "infinitely small" particles, if the nuclear explosion (point *E*) is implemented in it; it collapses into fragments if the explosion in it is initiated by a different quantity of explosive substances (line *CDE*). The moment of disintegration of a solid into atoms (elementary particles, etc.) is denoted by the symbol (✺).

The second stage (*translimiting states*) can be described in two ways. Either the analysis of the *average size* $d_D^* \to d_{\text{ll}}$ of *disintegration particles* is used [formulas (2.80), (2.81)] and represented by the curve CD_dE_d in Fig. 2.24 [note that in this case, the origin of coordinates is shifted to the point *C* and the size d_D^* ranges from 1 to 0 (line *CC'*)], or the damageability analysis $\psi_u^{eff} \to$ ll is used and represented by the curve $CD_\omega E_\omega$ in Fig. 2.24 (remind that here the "number of damages" corresponding to the disintegration (breakdown) of the system is designated by the number ψ conventionally equal to the number of atoms in the system.

The potentiality of the *parametric analysis* appears to be interesting and beneficial.

In our opinion, the representations as set forth above do not contradict the known and approved theories and the experimental results.

From Fig. 2.24 it is possible to find *two important features* of the time *A*-evolution of systems with respect to damageability.

First feature: the plot reveals the *sacramental point*, at which three special—critical units $\psi_u^{eff} = \omega_\Sigma = 1 = \omega_c, t/T_\oplus = 1$ and $d_\psi = 1 = d_c$ "come together". It is the *evolution epicenter*, or its *apotheosis*. These critical units also define the "*division*" of *A*-evolution into two essentially differing stages—*development stage*

ABC and *degradation stage CDE*. It is the point when the system loses all its functions, i.e., the point of transition to various translimiting states.

Second feature: using the plot in Fig. 2.24, it is obviously possible to describe and define the *effective energy conservation law*.

$$\int_0^{T_\oplus} u_\Sigma^{eff}(t)dt \equiv \int_{T_\oplus}^{T_*} u_{eff}^{\Sigma}(t)dt, \tag{2.89}$$

where $u_\Sigma^{eff}, u_{eff}^{\Sigma}$ is the effective energy on the first (development) and on the second (degradation) stages, respectively. The statement of this law is as follows: *effective energy absorbed by the system in the process of reaching the limiting (critical) state is identically equal to the released (scattered) effective energy in the process of degradation up to disintegration* (for example, into atoms).

Geometrically, this law requires the equality of the three areas in Fig. 2.24

$$S_{ABCC'} \equiv \varphi S_{C'CD_dE_d} \equiv S_{CD_\omega E_\omega E'}, \tag{2.89a}$$

where ϕ is the function of parameter transformation [for example, according to (2.81)].

Identities (2.89), (2.89a) express the *so-called sufficiency principle*. If it is violated, then it means that the energy u_Σ^{eff} supplied to the system prior to its limiting state (u_0) was larger than it was needed to achieve the mentioned state, i.e., it was *excessive* $(u_\Sigma^{eff} > u_0)$.

From the above-stated, three main conclusions follow:

1. *Damages are the fundamental physical property* (*and the functional duty*) *of any system and all of its elements.*
2. *Damageability of each object* (*any existing one*) *inevitably grows up to its breakdown—decomposition* (*disintegration*) *into a set of particles of arbitrarily small size, i.e., it is the unidirectional process of time:*

$$\begin{cases} \Psi_\Sigma^U = \Psi_\Sigma^U\left(\sigma_n^{(V,W)}, \varepsilon_n^{(V,W)}, T_\Sigma, V_{ij}, V_{ijT}, V_0, Ch, \Lambda_{i\backslash j}, m_k, t, u_0\right) \Rightarrow \hbar, \end{cases} \tag{2.90}$$

$$d^*_{D} \xrightarrow{\bar{t}} d_\hbar. \tag{2.91}$$

3. *Not only the unity and struggle of opposites but also the directivity of various and complex physical processes of hardening-softening* (*depending on the level of loads and time*) *are typical of the system evolution by damageability. It means that the* Λ*-function of damage interactions* (*of all kinds*) *can take three classes of values:* (1) $\Lambda < 1$ when the hardening process is dominant; (2) $\Lambda > 1$ when the

softening process is dominant; (3) $\Lambda = 1$ when a stable hardening-to-softening process ratio is found.

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