HANDBOOK
OF
MECHANICAL PROPERTIES
OF STRUCTURAL MATERIALS
AT A COMPLEX STRESS STATE

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Preface to the English translation

Severe stress conditions of present-day structures and strict limitations on their material consumption call for continuous refining of the methods of strength analysis and optimization of the technologies employed. The progress in creating rational structures and developing new efficient manufacturing processes depends primarily on the level of our knowledge of mechanical properties of the materials used. For this reason, much attention has always been paid to the accumulation of information in this field.

Unfortunately, the handbooks published in many countries contain only standard characteristics of the mechanical properties of materials obtained mainly in uniaxial tension and uniaxial compression, though it is known that in most cases the material of the carrying structural components works under conditions of a complex stress state.

This situation has repeatedly been the subject of discussions at numerous representative scientific forums and meetings of practical orientation. Yet in view of the difficulties associated with the methods of testing under multiaxial loading, particularly under conditions of high and low temperatures, one can still feel a serious shortage of reliable data on the regularities of deformation and fracture of structural materials under a complex stress state.

It should be noted that serious investigations involving this aspect of experimental mechanics have been performed in Ukraine, Russia, and other East European countries. As far back as the 1950s, the first testing machine for combined loading was created under the supervision of A.A. Ilyushin (Moscow). It made it possible to obtain unique experimental results on physical justification of new hypotheses and postulates which formed the basis of the theory of the material ultimate state and the theory of plasticity being developed. Beginning in 1960 systematic experimental investigations in the field of theories of plasticity have been carried out at the Institute for Problems of Strength of the National Academy of Sciences of Ukraine (Kiev). Here automated systems were created which enable materials to be tested under complex stress conditions over the temperature range from 30 to 1600 K. A great scope of experimental works was performed at the Institute of Mechanics of the National Ac. Sci. of Ukraine, the Institute for Problems of Mechanics of the Russian Ac. Sci. (Moscow), National Technical University of Ukraine (Kiev), and at other institutions. Unfortunately, the results of those investigations are little known in the West European countries and in the United States and this often leads to duplicating complicated tests and obtaining the already known relationships.

To the best of our knowledge, the first handbook containing extensive information on the influence of the stress state on the material properties was compiled by the authors and published in 1983 by Naukova Dumka Publishers (Kiev, Ukraine) in 3,000 copies. The handbook was sold out quickly, and at present it is a bibliographical rarity.

Since publication of the first edition, much new information has been obtained on the mechanical properties of various structural materials under conditions of a complex stress state, including low- and high-temperature behavior. The authors were constantly concerned with the accumulation and systematization of those data, taking them from the publications in periodical literature, proceedings of scientific conferences, and meetings, and using the results of their own investigations.

The main goals and tasks of the Handbook were highlighted in the preface to the Russian edition. In the preparation of the present edition, the overall trend of the book and the order in which the material is presented are left unchanged wherever possible. The introductory part regarding general problems of the mechanics of materials and methods of their testing is presented in a rather concise form without rigorous proofs or a lengthy journey into the history of the subject. This is reasonably compensated for by the extensive bibliography at the end of the book which allows a reader to form an objective idea about the stages in the development of one of the most important branches of the science concerned with material properties, and about the original works in this field, as well as about the pioneer investigators.

The bank of experimental data presented in the Handbook involves the results of testing only the most typical homemade materials. We consider this limitation justified because it is impossible to study all the materials known in the world due to their enormous quantity. Moreover, this would be unreasonable because the regularities of the deformation and fracture of the materials considered are the fundamental results and can be extended to any material of the corresponding class. Thus, in most cases, this rules out the necessity of organizing additional expensive tests which yield no qualitatively new results, or reduces appreciably their scope.

The authors tried to make the Handbook more complete and up-to-date by including new experimental data which reflect the latest achievements in the issues in question. Moreover, the authors took into account all the readers' remarks, acceptable in their opinion, which had been received after the publication of the first edition. In particular, in some cases, formats for presentation of the data on the effect of the stress state mode on the mechanical properties of materials were changed. This made them clearer and more convenient for use by researchers in refining the tools of the mechanics of a deformable solid, and by design engineers in selecting materials most acceptable for the structures designed, as well as in constructing the computation algorithms.

Additions were made to all sections of the Handbook. The most essential of them are the following.

1. Additional information has been introduced on the characteristics of strength and plasticity of materials of various classes under three-dimensional (triaxial) stress conditions, and three-dimensional compression in particular, which makes it possible to specify and to choose with a higher degree of justification the models of deformation and the criteria of strength of quasi-brittle materials used in practical calculations.

2. Important additions have been made to the results of studying the lifetime of structural materials under conditions of high-cycle loading and complex stress state.

3. The problems related to the influence of the stress state mode on the material crack growth resistance have been considered in more detail.

4. For the majority of homemade materials, their analogues (in chemical composition or mechanical properties) produced in the United States are presented. All the numerical results have been converted to the metric system.

The authors hope that with all these additions and amendments the Handbook will be more exhaustive in its content and will satisfy the needs of a wide circle of American and Western European specialists in the mechanics of materials concerned with various aspects of the theories of plasticity and strength, and researchers, engineers, and technicians engaged in designing machines and engineering structures.

The topicality of the material generalized in the Handbook seems to be unquestionable for scientific and technical workers. In this respect, it is pertinent to quote the following wise words belonging to Russian Academician I. Pavlov: "No matter how perfect the wing of a bird is, it would have never brought the bird high into the sky without the support of the air. Facts are the air for a scientist, without them you'll never be able to take wing. Without them your theories are vain attempts."

This book would have never appeared without the initiative and support of Mr. W. Begell and his colleagues. The authors would like to express their appreciation to V. Bastun, Dr. Sci.

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The authors will be grateful for any further remarks and comments to the second edition of the Handbook.

The authors

Preface to the Russian edition

High reliability of engineering structures and optimization of the technological process parameters depend to a great extent on the availability of the appropriate information on physicomechanical properties of the materials used.

In recent years, a great body of data has been accumulated on standard mechanical characteristics of materials of various classes and corresponding literature has been published which makes the work of a design engineer somewhat easier. However, these data cannot satisfy the ever growing requirements on the reliability of strength analysis, particularly for those structural elements which are subject to a variety of mechanical and thermal loads responsible for the complex stress state of the material. Intensive studies of the regularities of deformation and fracture of materials under conditions of a complex stress state are under way both in the Soviet Union and abroad. They are aimed at the development of scientifically justified codes for strength and reliable methods for predicting the deformability and ultimate state of critical elements of engineering structures. These investigations yield extensive factual data used efficiently not only by designers in their practical work but also by researchers engaged in the development of phenomenological models of the mechanics of deformable solids. Numerous requests from factories, design bureaus, and research institutions for the results of testing particular structural materials or for respective publications addressed to the Institute for Problems of Strength of the Ukr. SSR Ac. Sci., where the most sophisticated methods have been developed and the required equipment for testing materials has been designed and manufactured, testify to the topicality of this information.

This Handbook is the first attempt to systematize the results of the aforementioned investigations and to present them in a form (plots, tables) convenient for use. Testing of materials under complex stress conditions involves considerable procedure-related difficulties due to restrictions imposed by the design of specimens, loading schemes and regimes, and due to the virtually complete absence of industrial testing equipment. In addition, no unified terminology and notations have been established, and what is more, the data on the materials and types of tests given in the literature are not comparable in volume and classes. This explains the specific arrangement of the basic reference material in the book. To facilitate its perception, at the beginning of the book the authors give a brief survey of the main issues of the mechanics of a continuum pertaining mainly to the theory of stress and strains, and describe strength criteria and methods of material testing at a complex stress state.

The reference material is fully based on the results of the investigations performed in our country, particularly those performed by the authors during the past 15 years at the Institute for Problems of Strength of the Ukr. SSR Ac. Sci. This is partly explained by the fact that foreign publications refer to structural materials which are practically not used in the mechanical engineering in our country.

Wherever possible, the information is presented in the form in which it appeared in the primary source. When selecting the data, the authors faced essential difficulties connected with bringing them to a single system of units and making the terminology and notations consistent. We were not always successful in finding out the degree of accuracy of the results given in the primary sources. Therefore, some of the published data obtained with equipment not instrumented properly were not included into the Handbook. The authors' choice was also based on the practical value of the data with special emphasis on the results of short-term static tests under conditions of simple loading. In some cases, the test regime (e.g., under conditions of static or dynamic fatigue) was specified. To make the presentation of the material concise, all the explanations, including the description of testing equipment and procedures, are reduced to a minimum. However, the system of references in the tables and captions to figures makes it possible to obtain additional information if necessary.

The reference data are compiled by classes of materials (see Section 2: cast irons, carbon steels, etc.). The summary index (see Table 4), wherein these data are systematized by grades of materials, gives the numbers of figures and tables containing information on the regularities of deformation, plasticity, and strength of materials under complex stress conditions, as well as the literature sources from which this information has been taken and where the testing equipment and procedures used for obtaining the corresponding experimental data are described.

In accordance with the State standard GOST 8.310-78, the data presented in this Handbook fall into the category of reference data.

The authors are far from believing that the choice of the structure of this book is the best. They recognize that some important experimental findings may have been inadvertently overlooked, and new data are being generated.

The authors will be grateful for any remarks and suggestions regarding improvements and additions.

The authors

NOMENCLATURE

D_{out}, D_{in}	outer and inner diameters of tubular specimens
D_ε, D_σ	strain and stress deviators, respectively
E	Young's modulus
F_o, F, F_c	original, current, and limiting (in the neck) cross-sectional areas of a specimen
G	shear modulus
h	thickness of a flat specimen or of the wall of a tubular specimen
I_1, I_2, I_3	the first, second, and third invariants of the stress tensor
I_1', I_2', I_3'	the first, second, and third invariants of the stress deviator
I, k_σ	parameters of the stress state rigidity: $I = 3k_\sigma$, $k_\sigma = \dfrac{\sigma_o}{\sigma_i}$
K_o	bulk modulus
M_T, M_b	twisting and bending moments
N	axial load
p	pressure of the working medium (gas or liquid)
S_{1c}, S_{2c}, S_{3c}	ultimate principal normal stresses calculated from real dimensions of a specimen at the instant of fracture
s, s_c	current and ultimate reduction of the specimen cross-sectional area, $s = \ln F_o/F$; $s_c = \ln F_o/F_c$
T_ε, T_σ	strain tensor and stress tensor
T_ε^o, T_σ^o	spherical strain tensor and spherical stress tensor
γ_{12}, γ_{23}, γ_{31}	principal shear strains
γ_{xy}, γ_{yz}, γ_{zx}	shear strains in the planes xy, yz, and zx
$\gamma_{z\theta}$, $\gamma_{\theta r}$, γ_{rz}	shear strains in tubular specimens in the planes $z\theta$, θr, and rz
γ_{max}	maximal shear strain
γ_{oct}	octahedral shear strain
γ_i	shear strain intensity
$\dot{\gamma}_i$	shear strain rate intensity
γ_u	uniform limiting shear strain in pure torsion
$\gamma_{z\theta u}$, $\gamma_{\theta ru}$, γ_{rzu}	limiting shear strains in tubular specimens under multicomponent loading
γ_{umax}, γ_{uoct}	ultimate values of maximal strains and octahedral strains
γ_{iu}	ultimate value of the shear strain intensity
γ_{cmax}	maximal ultimate shear strain in the site of fracture
γ_a	amplitude value of the shear strain
δ	relative elongation after fracture in uniaxial tension
ε_1, ε_2, ε_3	principal linear strains
ε_x, ε_y, ε_z	strains in the x, y, and z directions
ε_z, ε_θ, ε_r	axial, circumferential, and radial strains in tubular specimens
ε_o	mean strain
$\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_3$	strain rates

ε_i	strain intensity
$\dot{\varepsilon}_i$	strain rate intensity
ε_a	amplitude strain value under cyclic loading
ε_{ia}	amplitude strain intensity value under cyclic loading
ε_u	uniform limiting strain in uniaxial tension
$\varepsilon_{1u}, \varepsilon_{2u}, \varepsilon_{3u}$	uniform limiting principal plastic strains at a complex stress state
$\varepsilon_{zu}, \varepsilon_{\theta u}, \varepsilon_{ru}$	uniform limiting plastic strains in tubular specimens
$\varepsilon_{1c}, \varepsilon_{2c}, \varepsilon_{3c}$	ultimate plastic strains in the site of fracture
$\varepsilon_{u\max}, \varepsilon_{c\max}$	maximal uniform and ultimate strains, respectively
$\varepsilon_{iu}, \varepsilon_{ic}$	limiting value of uniform strain intensity and ultimate plastic strain intensity, respectively
ε_{oct}	octahedral normal strain
$\varepsilon_{1t}, \varepsilon_{2t}, \varepsilon_{3t}$	limiting principal strains in creep
$\theta_1, \theta_2, \theta_3$	the first, second, and third invariants of the strain tensor
θ_o	relative volume change
μ	Poisson's ratio
$\mu_\sigma, \mu_\varepsilon$	parameters of the stress and strain deviator types (Lode's parameters)
ν	coefficient of transverse strain in the elastoplastic range
$\sigma_1, \sigma_2, \sigma_3$	principal normal stresses
$\sigma_x, \sigma_y, \sigma_z$	normal stresses on the planes perpendicular to the axes $x, y,$ and z
$\sigma_z, \sigma_\theta, \sigma_r$	axial, circumferential, and radial normal stresses in a tubular specimen
σ_o	mean normal stress
σ_i	stress intensity
σ_{oct}	normal octahedral stress
σ_p	proportional limit in uniaxial tension
$\overset{+}{\sigma}_{02}, \overset{-}{\sigma}_{02}$	yield strengths in tension and compression determined by an offset residual strain of 0.2 %
σ_u^+, σ_u^-	ultimate strength in uniaxial tension and compression, respectively
$\bar{\sigma}_u^+, \bar{\sigma}_u^-$	true ultimate strength in uniaxial tension and compression calculated by the maximal load considering real dimensions of a specimen
$\sigma_{1p}, \sigma_{2p}, \sigma_{3p}$	stresses corresponding to a proportional limit under a complex stress state
$\sigma_{1y}, \sigma_{2y}, \sigma_{3y}$	stresses corresponding to the yield strength under a complex stress state
σ_{iy}	yield strength determined from the generalized curve $\sigma_i = \sigma_i(\varepsilon_i)$ by an offset residual strain of 0.2 %
$\bar{\sigma}_{1u}, \bar{\sigma}_{2u}, \bar{\sigma}_{3u}$	true stresses corresponding to the maximal load under a complex stress state
$\sigma_{1u}, \sigma_{2u}, \sigma_{3u}$	conventional stresses corresponding to the maximal load under a complex stress state
$\bar{\sigma}_{iu}$	true value of the stress intensity corresponding to the maximal load
σ_t^+, σ_t^-	long-term strength in tension and compression
$\sigma_{1t}, \sigma_{2t}, \sigma_{3t}$	stresses corresponding to the long-term strength under a complex stress state

σ_a, σ_m	stress amplitude and mean stress under cyclic uniaxial loading, respectively
σ_{ia}, σ_{im}	stress amplitude intensity and mean stress intensity under cyclic loading
σ_{-1b}	fatigue limit under fully reversed loading in bending
τ_{12}, τ_{23}, τ_{31}	principal shear stresses
τ_{xy}, τ_{yz}, τ_{zx}	shear stresses on planes perpendicular to the y, z, and x axes and parallel to the x, y, and z axes, respectively
τ_u	ultimate strength in torsion
τ_y	yield strength in torsion
$\tau_{z\theta}$	shear stress in a tubular specimen
τ_p	proportional limit in torsion
τ_{oct}	octahedral shear stress
τ_{octm}	mean value of shear octahedral stress under cyclic loading
τ_{max}	maximal shear stress
τ_{umax}, τ_{uoct}	limiting values of the maximal and shear octahedral stresses
τ_{-1}	fatigue limit in torsion
τ_o	fatigue limit in pulsating torsion
ψ, ψ_u	local (in the neck) and uniform reduction of the cross-sectional area after fracture in uniaxial tension

1. STRENGTH CRITERIA AND METHODS OF MATERIAL TESTING UNDER A COMPLEX STRESS STATE

1.1. Parameters of the material stress-strain state

The stress-strain state of the material at a given point of a body subjected to the action of some forces (e.g., mechanical, thermal) is defined completely if the stress and strain tensors at this point are specified:

$$T_\sigma = \begin{vmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{vmatrix}, \quad T_\varepsilon = \begin{vmatrix} \varepsilon_x & \frac{1}{2}\gamma_{xy} & \frac{1}{2}\gamma_{xz} \\ \frac{1}{2}\gamma_{yx} & \varepsilon_y & \frac{1}{2}\gamma_{yz} \\ \frac{1}{2}\gamma_{zx} & \frac{1}{2}\gamma_{zy} & \varepsilon_z \end{vmatrix}. \tag{1}$$

When the stress-strain state of a body is nonuniform, the components of the stress and strain tensors are functions of the coordinates of the points.

By the law of reciprocity (twoness of shear stresses) first formulated and proved by Cauchy, to determine completely the stress state at the point considered, it is sufficient to know six stress tensor components and not nine:

$$\sigma_x, \sigma_y, \sigma_z, \quad \tau_{xy} = \tau_{yx}, \quad \tau_{yz} = \tau_{zy}, \quad \tau_{zx} = \tau_{xz}.$$

The stress-strain state at a point can be described by three principal normal stresses σ_1, σ_2, and σ_3 acting in three mutually perpendicular planes, which pass through the point considered, and by three principal strains ε_1, ε_2, and ε_3. Note that when the body considered is isotropic, the directions of principal strains coincide with the corresponding directions of principal stresses. This rule can be violated under specific conditions of deformation, e.g., under complex loading accompanied by a change in the ratio between the stress tensor components.

The relation between the principal stresses at a point and the stresses on an arbitrary oriented plane passing through this point is described by the following cubic equation:

$$\sigma^3 - I_1 \sigma^2 + I_2 \sigma - I_3 = 0, \tag{2}$$

where

$$\begin{aligned} I_1 &= \sigma_x + \sigma_y + \sigma_z = \sigma_1 + \sigma_2 + \sigma_3, \\ I_2 &= \sigma_x \sigma_y + \sigma_y \sigma_z + \sigma_z \sigma_x - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{zx}^2 = \sigma_1 \sigma_2 + \sigma_2 \sigma_3 + \sigma_3 \sigma_1, \\ I_3 &= \sigma_x \sigma_y \sigma_z + 2\tau_{xy} \tau_{yz} \tau_{zx} - \sigma_x \tau_{yz}^2 - \sigma_y \tau_{zx}^2 - \sigma_z \tau_{xy}^2 = \sigma_1\sigma_2\sigma_3. \end{aligned} \tag{3}$$

The roots of this equation are the principal normal stresses. Since the principal stresses do not change with a turn of the coordinate axes, i.e., they are independent of the method of their determination, the coefficients I_1, I_2, and I_3 from Eq. (2) are also independent of the choice of a coordinate system; in other words, they are stress tensor invariants with respect to the turn of the coordinate axes.

In addition to expressions (3), there are other combinations of the stress tensor components which are invariant to the turn of the coordinate axes. Yet all of them can be represented as functions of the three invariants presented above. Strictly speaking, any function of the three principal stresses is invariant with respect to the coordinate system, i.e., it can be called the invariant of the stress state.

The general case of the stress situation at a point can be considered as the stress state with the stress components related only to distortion and to hydrostatic tension-compression superimposed, which predetermines a change in the volume (dilatation). This allows us to present the stress tensor in the form of two components

$$T_\sigma = T^{\circ}_{\sigma} + D_\sigma ,$$

where T°_{σ} is the spherical stress tensor composed of the components which are related to the dilatation:

$$T^{\circ}_{\sigma} = \begin{vmatrix} \sigma_o & 0 & 0 \\ 0 & \sigma_o & 0 \\ 0 & 0 & \sigma_o \end{vmatrix} ,$$

and D_σ is the stress deviator composed of the components which are related to the distortion :

$$D_\sigma = \begin{vmatrix} \sigma_x - \sigma_o & 0 & 0 \\ 0 & \sigma_y - \sigma_o & 0 \\ 0 & 0 & \sigma_z - \sigma_o \end{vmatrix} .$$

Since the first invariant of the spherical tensor coincides with the first invariant of the stress tensor

$$I^{\circ}_{1} = \sigma_o + \sigma_o + \sigma_o = 3\sigma_o = \sigma_x + \sigma_y + \sigma_z = I_1 , \tag{4}$$

the first invariant of the stress deviator is equal to zero, i.e.,

$$I'_1 = (\sigma_x - \sigma_o) + (\sigma_y - \sigma_o) + (\sigma_z - \sigma_o) ,$$

and the second one is calculated by the formula

$$I'_2 = \frac{1}{6}\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6 \, (\tau^2_{xy} + \tau^2_{yz} + \tau^2_{zx}) \right] . \tag{5}$$

In expression (1) the components of the strain tensor are not total shears (angular strains) but their halves. In this case, the theory of strain state appears to be similar to the theory of stress state. The principal strains $\varepsilon_1 \geq \varepsilon_2 \geq \varepsilon_3$ are found as the roots of a cubic equation

$$\varepsilon^3 - \theta_1 \, \varepsilon^2 + \theta_2 \, \varepsilon - \theta_3 = 0 .$$

solved for ε. The values θ_1, θ_2, and θ_3 are called, respectively, the first, second, and third invariants of the strain tensor and are expressed in terms of strains as follows:

$$\theta_1 = \varepsilon_x + \varepsilon_y + \varepsilon_z = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 ,$$

$$\theta_2 = \varepsilon_x \, \varepsilon_y + \varepsilon_y \, \varepsilon_z + \varepsilon_z \, \varepsilon_x - \frac{1}{4} \, (\gamma^2_{xy} + \gamma^2_{yz} + \gamma^2_{zx}) = \varepsilon_1 \, \varepsilon_2 + \varepsilon_2 \, \varepsilon_3 + \varepsilon_3 \, \varepsilon_1 ,$$

$$\theta_3 = \varepsilon_x \, \varepsilon_y \, \varepsilon_z + \frac{1}{4} \, (\gamma_{xy} \, \gamma_{yz} \, \gamma_{zx} - \varepsilon_x \, \gamma^2_{yz} - \varepsilon_y \, \gamma^2_{zx} - \varepsilon_z \, \gamma^2_{xz}) = \varepsilon_1 \, \varepsilon_2 \, \varepsilon_3 .$$

Similarly to the stress tensor, the strain tensor is resolved into a spherical strain tensor

$$T^{\circ}_{\varepsilon} = \begin{vmatrix} \varepsilon_o & 0 & 0 \\ 0 & \varepsilon_o & 0 \\ 0 & 0 & \varepsilon_o \end{vmatrix}$$

and a strain deviator

$$D_\varepsilon = \begin{vmatrix} \varepsilon_x - \varepsilon_o & \frac{1}{2}\gamma_{xy} & \frac{1}{2}\gamma_{xz} \\ \frac{1}{2}\gamma_{yx} & \varepsilon_y - \varepsilon_o & \frac{1}{2}\gamma_{yz} \\ \frac{1}{2}\gamma_{zx} & \frac{1}{2}\gamma_{zy} & \varepsilon_z - \varepsilon_o \end{vmatrix} .$$

A strain deviator defines the degree to which a given strain state described by the strain tensor deviates from hydrostatic tension-compression at the principal strains equal to the arithmetic mean of the linear strains of the strain state considered.

Thus, if a body is in a uniform strain state described by a spherical strain tensor, the shape of the body does not change. When the strain state is described by a strain deviator, the volume does not change. The expressions for the invariants of the spherical strain tensor and strain deviator can be written by analogy with expressions (4) and (5).

From the condition of equilibrium of an elementary tetrahedron, for which the direction of the normals to its lateral faces coincides with that of the principal axes and the normal to the inclined plane makes angles α, β, and γ with the coordinate axes, follows

$$\cos\alpha = \frac{\sigma_x}{\sigma_1}, \quad \cos\beta = \frac{\sigma_y}{\sigma_2}, \quad \cos\gamma = \frac{\sigma_z}{\sigma_3}.$$

Taking the square and adding, we obtain the equation of the Lame ellipsoid

$$\frac{\sigma_x^2}{\sigma_1^2} + \frac{\sigma_y^2}{\sigma_2^2} + \frac{\sigma_z^2}{\sigma_3^2} = 1 ,$$

with the ends of the vectors of the total stresses for the planes passing through the point considered lying on its surface. The axes of the ellipsoid coincide with the directions of the principal normal stresses.

It can be shown that there are three pairs of planes where the shear stresses reach the extremum. These extreme values of the shear stresses are called the principal shear stresses:

$$\tau_{12} = \frac{\sigma_1 - \sigma_2}{2}, \quad \tau_{23} = \frac{\sigma_2 - \sigma_3}{2}, \text{ and } \tau_{31} = \frac{\sigma_3 - \sigma_1}{2} .$$

The plane inclined equally to the principal axes ($\alpha = \beta = \gamma$) is called octahedral. The normal stress on this plane is equal to the arithmetic mean of the three principal normal stresses

$$\sigma_{oct} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} = \sigma_o , \tag{6}$$

whereas the shear stress on the same plane is equal to the root mean square of the three principal shear stresses

$$\tau_{oct} = \frac{2}{3}\sqrt{\tau_{12}^2 + \tau_{23}^2 + \tau_{31}^2} .$$

This formula can also be presented in the form

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \tag{7}$$

or

$$\tau_{oct} = \frac{\sqrt{2}}{3} \sqrt{(\sigma_1 + \sigma_2 + \sigma_3)^2 - 3(\sigma_1 \sigma_2 + \sigma_2 \sigma_3 + \sigma_3 \sigma_1)} .$$

The stresses on octahedral planes can also be expressed in terms of six stress tensor components. In this case, the expressions for σ_{oct} and τ_{oct} have the form

$$\sigma_{oct} = \frac{\sigma_x + \sigma_y + \sigma_z}{3} , \tag{8}$$

$$\tau_{oct} = \frac{1}{3} \sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6 \, (\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)} . \tag{9}$$

From expressions (6) and (7) it can be seen that octahedral normal stress is proportional to the first invariant of the stress tensor and shear octahedral stress depends on both the first and the second invariants. Comparing expressions (8) and (9) with (4) and (5), we find

$$\sigma_{oct} = \frac{1}{3} I_1 ,$$

$$\tau_{oct} = \frac{\sqrt{2}}{2} \sqrt{I_1^2 - 3I_2} .$$

Octahedral normal stresses, which are equal on all eight faces of the octahedron, induce the change in its volume:

$$\frac{\Delta V}{V} = \theta_1 = 3 \, \varepsilon_{oct} ,$$

where ε_{oct} is the octahedral normal strain equal to the mean relative strain:

$$\varepsilon_{oct} = \frac{\varepsilon_1 + \varepsilon_2 + \varepsilon_3}{3} = \varepsilon_o .$$

Linear octahedral strain in the direction of a normal to the face of the octahedron leads to the change in the initially right angle between the normal to the face and the plane of the face. Octahedral shear strain is determined from the formula

$$\gamma_{oct} = \frac{2}{3} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_1 - \varepsilon_3)^2}$$

or (when the axes of the octahedron do not coincide with the principal axes)

$$\gamma_{oct} = \frac{2}{3} \sqrt{(\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2 + \frac{2}{3} \, (\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2)} .$$

In the solution of a number of problems of mechanics of materials it appeared convenient to use generalized stresses and generalized strains which are proportional to octahedral shear stresses and octahedral shear strains:

$$\sigma_i = \frac{3}{\sqrt{2}} \tau_{oct} = \frac{\sqrt{2}}{2} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} ,$$

$$\varepsilon_i = \frac{\sqrt{2}}{2} \gamma_{oct} = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2} .$$

Stress intensity and strain intensity have no physical meaning since they cannot be defined as stresses and strains acting on any plane. However, compared to other complex characteristics of a stress-strain state, these parameters have some advantages. For instance, in uniaxial tension ($\sigma_1 = \sigma,\ \sigma_2 = \sigma_3 = 0$) stress intensity is equal to the tensile stress ($\sigma_i = \sigma$) and strain intensity at $\mu = 0.5$ equals to the strain in the direction of the applied force.

Stress intensity and strain intensity are quadratic functions of the characteristics of the stress-strain state. Their usage in calculations and in the processing of experimental data involves certain mathematical difficulties. For this reason, linear functions

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2} \quad \text{and} \quad \gamma_{max} = \varepsilon_1 - \varepsilon_3$$

are sometimes introduced instead of σ_i and ε_i. To reduce the error from such replacement, one can introduce a correction factor, which takes into account the type of the stress state, and use more accurate relationships. An expression for this factor can be obtained through the following elementary transformations:

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2} = \frac{(\sigma_1 - \sigma_3)\,\sigma_i}{2\sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1\sigma_2 - \sigma_2\sigma_3 - \sigma_3\sigma_1}} =$$

$$= \frac{(\sigma_1 - \sigma_3)\,\sigma_i}{\sqrt{3(\sigma_1 - \sigma_3)^2 + (2\sigma_2 - \sigma_1 - \sigma_3)^2}} = \frac{\sigma_i}{\sqrt{3 + \left(\frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}\right)^2}} = \frac{1}{\sqrt{3 + \mu_\sigma^2}} \cdot \sigma_i .$$

By analogy

$$\gamma_{max} = \varepsilon_1 - \varepsilon_3 = \frac{3(\varepsilon_1 - \varepsilon_3)\,\varepsilon_i}{2\sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 - \varepsilon_1\varepsilon_2 - \varepsilon_2\varepsilon_3 - \varepsilon_3\varepsilon_1}} =$$

$$= \frac{3\varepsilon_i}{\sqrt{3 + \left(\frac{2\varepsilon_2 - \varepsilon_1 - \varepsilon_3}{\varepsilon_1 - \varepsilon_3}\right)^2}} = \frac{3}{\sqrt{3 + \mu_\varepsilon^2}} \cdot \varepsilon_i .$$

Thus,

$$\frac{\sigma_i}{\tau_{max}} = \sqrt{3 + \mu_\sigma^2} \quad \text{and} \quad \frac{\varepsilon_i}{\gamma_{max}} = \frac{1}{3}\sqrt{3 + \mu_\varepsilon^2} , \tag{10}$$

where parameters

$$\mu_\sigma = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3} \quad \text{and} \quad \mu_\varepsilon = \frac{2\varepsilon_2 - \varepsilon_1 - \varepsilon_3}{\varepsilon_1 - \varepsilon_3} \tag{11}$$

are called the Lode-Nadai parameters or the parameters of the deviator type. The magnitudes of these parameters can vary from – 1 to + 1. And these particular magnitudes define the variation limits of relations (10):

$$\sqrt{3} \le \frac{\sigma_i}{\tau_{max}} \le 2, \qquad \frac{1}{\sqrt{3}} \le \frac{\varepsilon_i}{\gamma_{max}} \le \frac{2}{3} .$$

Mean values of these ratios are

$$\left|\frac{\sigma_i}{\tau_{max}}\right| = \frac{1}{2}(\sqrt{3}+2) = 1.866,$$

$$\left|\frac{\varepsilon_i}{\gamma_{max}}\right| = \frac{1}{2}\left(\frac{1}{\sqrt{3}}+\frac{2}{3}\right) = 0.622.$$

They differ from the extreme values by approximately 7 %. Thus any stress-strain state at a point can be determined by the stress and strain tensor components or by the population of their derivatives (σ_o, σ_i, μ_σ and ε_o, ε_i, μ_ε).

The parameters which characterize the stress-strain state have a specific geometrical interpretation in three-dimensional spaces σ_1, σ_2, σ_3 and ε_1, ε_2, ε_3, respectively.

Let us consider the space of stresses. The loading path in this space (Fig. 1) can be represented by the segment OM_i which is a population of successive locations of the point M in the process of loading. At certain critical values of the principal stresses the material limiting state will occur, e.g., the state corresponding to a given offset of the residual strain. By loading with different ratios of principal stresses, we shall get a population of points Q_i lying on the surface Q. This surface can be called the "limiting surface" since it bounds the region of the stress states (inside the surface) safe for preset conditions.

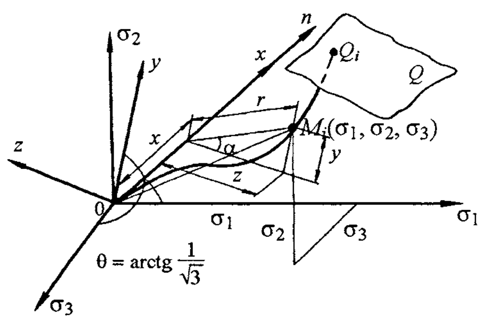

Fig. 1

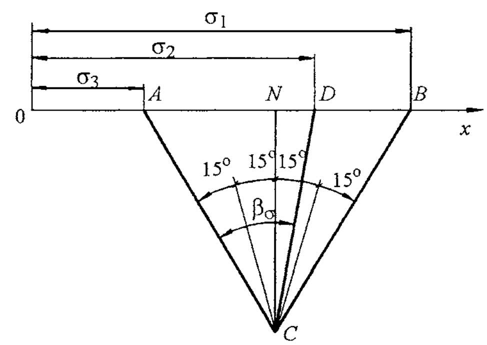

Fig. 2

Fig. 1. Limiting state surface of the material in the space of stresses.

Fig. 2. Geometrical interpretation of the stress state characteristics according to V.M. Rozenberg.

If OM is a straight line, loading occurs with a proportional increase in stresses. In this case, according to the classification of A.A. Ilyushin, a simple loading takes place. When point M is equidistant from the axes, then $\sigma_1 = \sigma_2 = \sigma_3$ and the stress state characterized by the coordinates of this point is called hydrostatic tension (if all the stress components are positive) or hydrostatic compression (if all the components are negative). Therefore, all the points of the ray ON equally inclined to the axes correspond to hydrostatic tension or compression.

In the system x, y, and z, whose axis Ox coincides with the diagonal of the stress space (Fig. 1), the coordinates of the point M considered (σ_1, σ_2, and σ_3) will be

$$x = \frac{1}{\sqrt{3}} (\sigma_1 + \sigma_2 + \sigma_3),$$
$$y = \frac{1}{\sqrt{2}} (\sigma_1 - \sigma_3),$$
$$z = \frac{\sqrt{3}}{\sqrt{2}} (\sigma_1 + \sigma_3) . \qquad (12)$$

By analogy, in the cylindrical coordinate system x, r, α we have

$$x = \frac{1}{\sqrt{3}} (\sigma_1 + \sigma_2 + \sigma_3),$$
$$r = \sqrt{y^2 + z^2} = \frac{1}{3} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \ ,$$
$$\alpha = \operatorname{arcctg} \frac{z}{y} = \operatorname{arcctg} \left(\frac{1}{\sqrt{3}} \cdot \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3} \right) = \operatorname{arcctg} \frac{\mu_\sigma}{\sqrt{3}} . \qquad (13)$$

Comparing relations (12), (7), (6), and (13) we obtain

$$\sigma_o = \frac{1}{\sqrt{3}} x , \quad \sigma_i = \frac{\sqrt{3}}{\sqrt{2}} r , \quad \mu_\sigma = \sqrt{3} \operatorname{ctg} \alpha .$$

Therefore, the stress state parameters σ_o, σ_i, and μ_σ correlate with the coordinates of the cylindrical system x, r, and α.

A convenient graphical interpretation of the parameters σ_o, σ_i, and μ_σ was proposed by V.M. Rozenberg and G.A. Smirnov-Alayev [349].

The segments *OA*, *OD*, and *OB* equal numerically (at a given scale) to the magnitudes of the principal normal stresses are laid off on the ray (Fig. 2). An equilateral triangle is constructed on the segment *AB*, whose length is equal to the maximum difference of the principal stresses $\sigma_1 - \sigma_3$, with this segment used as a base. If we join point *D*, which divides the segment *AB* in the ratio $\frac{\sigma_1 - \sigma_2}{\sigma_2 - \sigma_3}$, to the vertex *C* of the triangle, the length of the segment will be numerically equal (at a given scale) to the stress intensity value σ_i. Indeed,

$$CD = \sqrt{CB^2 - NB^2 + ND^2} = \sqrt{(\sigma_1 - \sigma_3)^2 + \left(\frac{\sigma_1 - \sigma_3}{2}\right)^2 + \left(\sigma_2 - \frac{\sigma_1 + \sigma_3}{2}\right)^2} =$$

$$= \frac{\sqrt{2}}{2} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} = \sigma_i .$$

The magnitude of the Lode-Nadai parameter will be defined as the ratio between the lengths of the segments *ND* and *NB*:

$$\frac{ND}{NB} = \frac{\sigma_1 - \frac{\sigma_1 + \sigma_3}{2}}{\frac{1}{2} (\sigma_1 - \sigma_3)} = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3} = \mu_\sigma .$$

The parameter μ_σ and the angle β_σ, which is equal to the angle *ACD*, are related unambiguously by the following equation:

$$\mu_\sigma = \frac{\operatorname{tg}(\beta_\sigma - 30°)}{\operatorname{tg} 30°}.$$

Similar construction can be used for graphical interpretation of the dependence of the strain state characteristics on the principal strains.

1.2. Limiting state criteria of materials

Basic information on the mechanical properties of materials is furnished by the data obtained by testing standard specimens in tension, compression, and pure shear (twisting of thin-walled pipes). To assess the material strength under service conditions, where the system of acting stresses can be arbitrary, the conditions of equivalence (strength criteria) are used which are based on the defining hypotheses and assumptions.

The problem of rational choice of the criterion is reduced to the determination of a function of the stress tensor components, e.g., of the form

$$K = \varphi(\sigma_1, \sigma_2, \sigma_3, m_i), \tag{14}$$

which at stresses corresponding to the material limiting state retains its magnitude irrespective of the ratio between the stress tensor components at which the loading is carried out. If this state corresponds to a given offset of residual strain, condition (14) is called the yield condition; when the state which precedes fracture is considered, we are speaking about the fracture condition. The K value, which is a strength criterion, sometimes has a specific physical interpretation: maximum normal or shear stress, maximum elongation, energy of distortion, etc.

The material constants m_i are determined from the results of testing under the simplest loadings by solving simultaneously the equations written in the form of (14) with respect to each of the tests performed.

For most criteria, the number of constants to be defined does not exceed three. Therefore, the material base tests are generally performed in uniaxial tension, uniaxial compression, and torsion. For these types of loading, condition (14) can be written in the form

$$\begin{aligned} \varphi_1 &= (\bar{\sigma}^+, m_i) = K, \\ \varphi_2 &= (\bar{\sigma}^-, m_i) = K, \\ \varphi_3 &= (\bar{\tau}, m_i) = K. \end{aligned} \tag{15}$$

Here and in what follows by $\bar{\sigma}^+$, $\bar{\sigma}^-$ and $\bar{\tau}$ are meant the elasticity limit, yield strength, or ultimate strength, respectively, in tension, compression, or torsion.

A system of equations (15) makes it possible to present initial constants as functions of the material characteristics under respective loadings.

Condition (14) in a three-dimensional space σ_1, σ_2, and σ_3 (Fig. 1) is interpreted by a surface which bounds the region of safe states. The limiting fracture surface is a locus whose coordinates are equal to the ultimate strengths, and points lying on the limiting surface of the plastic flow (or the limiting yield surface) correspond to the material yield strengths under different stress states. When one of the principal stresses is equal to zero, the limiting state will be described by a plane curve which, in this case, is called the "ultimate fracture curve" or "limiting yield curve".

In addition to the stress state, the material strength is influenced by temperature, stress gradients, size effects, and other factors. Therefore, surfaces of equal strength should have been

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