LONGEVITY OF CONSTRUCTIONAL MATERIALS IN THREE-DIMENSIONAL STRESS STATE

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Abstract

The study of longevity at different kinds of stress state was carried out for the case of hardened epoxide resin. The average longevity periods were obtained as a result of testing five identical specimens in different types of stress state by 21 loading trajectories sufficiently remote from one another. In all, there were tested 160 specimens at 293K.

The results were analysed using the kinetic concept of fracture in the form

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma I - \alpha L - \beta L^2}{RT}\right),$$

that describes well longevity in every stress state. Here t - time before fracture, τ_0 - pre-exponential factor; U_0 - activation energy; γ , α , β - structure-sensitive factors, I , L - stress invariants. The isochronic surfaces of longevity appear as rotational surfaces relative to the hydrostatic axis, because the above criterion for fixed time represents a rotational paraboloid relative to the coordinate L . The theoretical values of longevity for the three types of stress state are compared with experiment and present convincing evidence of the advantages of the proposed model.

The established rules of longevity of an epoxide resin for three-dimensional stress states permit the use of available test results for the construction of mathematical models. The reduced data must contain at least experimental data on uniaxial and (equal) biaxial tension as well as torsion at different hydrostatic pressures.

The longevity of different technical objects (machines and structures) is one of the most important technical-economical features. At the present rate of progress and development of science and technology, most technical objects have to be replaced or overhauled at least every ten years. The actual longevity must be well-grounded with optimal periods of service. In most branches of industry the fixed longevity does not achieve values optimal from the economical point of view, and for a number of products the actual resource turns out to be less than the fixed one and "good" must be replaced by "new".

One of many factors responsible for the actual resource of many elements of different technical objects is insufficient longevity of single elements conditioned by the lack of reliable experimental data on the long-term strength of constructional materials in an arbitrary stress state. Up to the present time this

did not permit the construction of reliable mathematical models (long-term strength criteria). In other words, we have an extremely paradoxical situation: in real structures the material is, as a rule, subjected to three-dimensional stress, while in laboratories up to now the processes responsible for the efficiency of constructional materials under operational conditions (i.e. different conditions of a three-dimensional stress state) have not yet been modeled and investigated.

In spite of the fact that the kinetic theory of strength /1,2/ was developed forty years ago, there are many unsettled questions concerning the problem of material longevity. Such a problem is the behaviour of the material under a three-dimensional stress state. For a long time longevity of polymeric materials was studied under uniaxial tensile conditions /2,3/. Then investigations under torsion were carried out /4,5/. Under uniaxial compression polymeric materials do not support the kinetic failure concept for presently unknown reasons /5/. Thus, after the expansion of studies on torsion, compression and other types of stress state, the new results have rather complicated the problem of longevity in an arbitrary (three-dimensional) stress state, than cleared it up. So, it became unclear why the coefficient γ in the Zhurkov formula depends on the deformation type (at first it was assumed that it is structurally sensitive) or, what is worse, why the kinetic concept of solid state failure does not manifest itself under uniaxial compression.

Here we must mention that the confusion in the experiments on uniaxial compression, when the load is transferred to the cylindrical or prismatic sample by solid stamps more stiff than the investigated material, was introduced long before the emergence of the kinetic failure concept.

Because of the special importance of this problem, let us consider the fracture of a solid state in uniaxial tension in more detail. It is usually supposed that in uniaxial compression two sides of an elementary cube (Fig. 1a) are uniformly

Fig. 1. Deforming scheme in uniaxial compression, when load is transferred by stiff stamps (a) and fluid (b).

loaded with only normal compressive stresses. At the same time it is considered (and so it has to be) that neither longitudinal nor transversal deformations depend on coordinates. In Fig. 1b the real pattern realized in the experiments on uniaxial compression is shown. For most polymeric materials under such compression the cylindrical sample takes a barrel shape already at a deformation of a few percent. This means that the transverse deformations are not equal along the sample length, showing a maximum in the center and tending to zero at the surface where the load is transferred to the sample with the help of a stiff stamp. Consequently, owing to the existence of friction forces on the butt-end surface of the sample, the real pattern of the stressed-deformed state is nonuniform and very far from the supposed one.

Thus, one must look for the answer to the question of inadequacy of the kinetic failure concept in compression in the inability to experimentally realize this pure deformation. It turned out that this is not a simple problem and in view of its complexity we shall return to it later. For the present we shall consider the possibilities of experimental techniques and a minimum number of measurements necessary for reliable identification of strength theories. The number of loading trajectories in the kinetic fracture aspect must at least permit determination of the form and dimensions of the isochronic surfaces of limiting resistance.

Fig. 2 shows some stress states that may relatively easily be realized with the help of the earlier developed apparatuses [8-12]. The first loading trajectory (a) is easily realized with uniaxial tension. The second trajectory (b) may be realized by torsion of a thin-walled tubular sample. The third trajectory (c) is obtained if the thin-walled tubular sample with bottoms is loaded with the internal pressure. At present, the axial σ_z and the tangential σ_θ stresses are determined by the

Fig. 2. Scheme of realization for different stress states. Explanations in the text.

sample dimensions (D - sample diameter, δ - its thickness) and the pressure ΔP in the following way:

$$\sigma_z = -\frac{\Delta P \cdot D}{4\delta} \quad (1); \quad \sigma_\theta = -\frac{\Delta P \cdot D}{2\delta} \quad (2).$$

The fourth trajectory (d) is realized /10/ with the help of the thin-walled tubular specimen, loaded simultaneously with internal pressure and an axial tensile force, when at every moment the value of the axial force ensures the fulfilment of the condition $\sigma_z = \sigma_\theta$. The considered four trajectories are realized with the help of four different testing machines at normal pressure. The realization of the next four trajectories (e, f, g, h) is possible only by two-parametric loading in the high pressure vessel.

Biaxial compression with equal compressive stresses (e) is easily achieved by simultaneous action of tensile stress and hydrostatic pressure on the bulk specimen, the absolute value of uniaxial stress at every moment being equal to the hydrostatic pressure value. If a thin-walled tubular sample is simultaneously loaded with torsion and hydrostatic pressure, the tangential stress being at every moment equal to the hydrostatic pressure, we obtain a stress state of the biaxial compression type with the ratio of main stresses equal to 2 (Fig.2f).

Pure shear deformation (Fig.2g) can be obtained by loading the thin-walled tubular specimen in the high pressure vessel with two pressures, a general pressure P and an excess pressure ΔP . The general pressure P produces overall compression in every point of the specimen when $\sigma_1 = \sigma_2 = \sigma_3 = P$ and the excess pressure ΔP produces two stresses determined by formulas (1) and (2). Summing the stresses produced by P and ΔP we obtain the stress state according to the scheme of Fig.2g. It is only necessary to mention that in the process of loading the pressure P must be equal to the stress σ_z .

The stress state of uniaxial compression (Fig.2h) under pure boundary conditions, when the load is transferred to the sides of an elementary cube by a liquid, is realized via three-parametric loading of the thin-walled tubular specimen with a general pressure P , an excess pressure ΔP transferred into the internal cavity of the specimen and a normal tensile force N . In order to realize the uniaxial compression, the process of loading must be carried out while retaining definite ratios between three loads: a) the pressure P producing the three-dimensional uniform compression (the third tensor in the left part of equation (3) below) may increase arbitrarily, b) the excess pressure ΔP and the normal force N must increase so that $|\sigma_\theta| = P$, and the normal force increases so that $\sigma_z + \sigma_p = \sigma_\theta$. In this case the sum of three tensors on the left side of (3) will be equal to the fourth one (on the right side), corresponding to uniaxial compression.

$$\begin{pmatrix} \sigma_z & 0 & 0 \\ 0 & \sigma_\theta & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} \sigma_p & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} -P & 0 & 0 \\ 0 & -P & 0 \\ 0 & 0 & -P \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -P \end{pmatrix} \quad (3)$$

The eight elementary cubes considered above with trajectories are showed in the plane $\sigma_1 \sigma_2$ (Fig.3). The eight experiments (listed in Fig.2) shown in this figure already give 12 loading trajectories, due to the isotropicity of the material. From Fig.3 it follows that the considered 12 trajectories are sufficient for the verification of strength theories, as all trajectories are very remote from one another and consequently provide maximum information. However, it should be mentioned that for complete analysis of the mechanical properties of polymeric materials it is necessary to have information about their behaviour in a three-dimensional stress state. For this purpose, let us consider what information we can obtain from the technical methods described above for polymeric material fracture.

Fig.3. Scheme of possible loading trajectories in plane stress state.

In the three-dimensional space of three main stresses σ_1 , σ_2 and σ_3 (Fig.4a), if we consider fracture as a critical phenomenon, there exists a certain surface (surface of limiting resistance) that divides the safe and dangerous state regions. The experimental determination of the form and dimensions of such a surface is of sufficient interest both from scientific and practical points of view. The scientific value of such results consists in the opening of a possibility of reliable verification of numerous hypotheses and assumptions concerning the physics and

Fig.4. Scheme of surface of limiting resistance (a) and possible loading trajectories (b) in three-dimensional stress state.

mechanics of fracture of polymeric materials in an arbitrary stress state. For the case of static loading such a problem has been considered in [17]. From the point of view of the kinetic theory of fracture, the surface of limiting state can change its form with time and move in the three-dimensional space. If the stress state in the point defined by three main stresses is inside this region, failure is impossible. As will be shown below, for most isotropic polymeric materials the surface of limiting resistance represents a rotational surface relative to the hydrostatic axis L (the axis passing through the origin and being equally inclined to the axes σ_1 , σ_2 and σ_3) and, consequently, it is possible to reduce the number of coordinates from three to two, L and I (coordinate I is perpendicular to L). Values of I and L are expressed in terms of the main stresses as follows:

$$I = \sqrt{\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2\right]} / \sqrt{3} \quad (4)$$

$$L = (\sigma_1 + \sigma_2 + \sigma_3) / \sqrt{3} \quad (5)$$

In order to establish the minimum number of experiments required to determine the form and dimensions of the surface of limiting resistance, 12 trajectories shown in Fig.3 for the plane stress state are represented in Fig.4b in coordinates I and L . In this figure the trajectories $O-O_1$ and $O-O_2$ correspond to overall compression and overall tension. The first trajectory is realized rather simply; however, in this deformation the isotropic polymers do not experience failure. The achievement of the second trajectory (overall tension) in a quasistatic arrangement has not yet succeeded. The region between the trajectories of overall tension and biaxial tension (0-4) is also unrealizable at present because of methodical difficulties. Seven trajectories from biaxial equal tension (0-4) to biaxial equal compression (0-5) are sufficient for the verification of strength criteria of arbitrary complexity. In the region of negative values of the parameter L it is possible to obtain an unlimited number of trajectories by tension (trajectory O_1-10) and torsion (O_2-9) at different values of hydrostatic pressure, determined by coordinate O_1 . It should only be mentioned that, if all experimental points are grouped near some curve, as for example in Fig.4b, only in this case the surface of limiting resistance is the rotational surface relative to the hydrostatic axis. If this condition is not satisfied, it may turn out that the considered experimental possibilities are not sufficient to establish the form and dimensions of the surface of limiting resistance and this problem is out of the frame of the present work. It thus follows from the foregoing that there exists a possibility of polymer fracture practically in every trajectory, excluding the first octant where all three main stresses are positive.

The study of longevity in different kinds of stress state was carried out for the case of a cured epoxide resin (Epon 828EEN Shell Co. - 100 m.p.+ XD-7114 Dow Chemical -10 m.p. + Triethanolamine - 10 m.p.). In Table 1 the data on resin fracture are presented: average longevity periods as a result of testing of five identical specimens in different types of stress state by 21 loading trajectories sufficiently remote from one another. Here the loading trajectory means the form of stress state with a fixed ratio between the three main stresses, e.g. a definite direction corresponds to axial tension and another direction corresponds to torsion. At the same time the value of the stress may be arbitrary and does not influence the position of the trajectory. In all there were tested 160 specimens at 293K (Table 1).

It follows from the foregoing that there is an infinite number of states and it is necessary to introduce reasonable limits on the number of measurements. First of all, let us proceed from the concept of polymer fracture preceding Zhurkov's work, when the fracture was considered as a critical phenomenon in both physics and mechanics. This assumption somewhat simplifies the problem of choosing the experimental volume and the construction of phenomenological longevity criteria for an arbitrary stress state. In this case, for the plane stress state seven experiments are sufficient, that allow the obtaining of the twelve points shown in Fig.3. Using twelve points for the plane stress state, it seems possible to verify well any strength criterion. For the three-dimensional stress state additional

Table I. Basic experimental data: longevity of epoxide resin in three-dimensional stress state.

No.	σ_1 , MPa	σ_2 , MPa	σ_3 , MPa	τ_E , s	τ_T / τ_E , s	No.	σ_1 , MPa	σ_2 , MPa	σ_3 , MPa	τ_E , s	τ_T / τ_E , s
1	73	0	0	8	0.80	28	-18	-36	-100	11,900	1.28
2	78	0	0	8	1.13	29	-20	-40	-100	38,600	1.31
3	67	0	0	8	0.65	30	-25	-50	-100	1,081,000	0.80
4	46	-46	-46	8	0.92	31	-45	-90	-150	2,670	0.46
5	0	-88	-88	8	1.02	32	-50	-100	-150	26,200	0.44
6	0	-108	-108	8	1.44	33	-55	-110	-150	1,782,000	0.48
7	0	-96	-96	8	1.44	34	0	-46	-92	830	1.32
8	-39	-100	-161	7	0.82	35	0	-43	-86	4,210	1.41
9	-130	-200	-270	10	1.35	36	0	-40	-80	25,260	1.26
10	-224	-300	-376	12	0.61	37	0	-37	-75	124,200	1.38
11	-1	-100	-100	7	0.67	38	0	-34	-69	944,000	1.10
12	-85	-200	-200	10	1.53	39	-135	-200	-265	250	1.48
13	-172	-300	-300	12	0.82	40	-138	-200	-262	3,660	0.78
14	75	37	0	26	1.11	41	-141	-200	-259	31,300	0.71
15	69	35	0	420	0.73	42	-144	-200	-259	237,000	0.73
16	63	32	0	2,630	1.22	43	-230	-300	-370	350	1.27
17	58	29	0	43,200	0.72	44	-233	-300	-367	3,250	1.06
18	52	26	0	428,000	0.75	45	-237	-300	-363	38,500	1.38
19	43	0	-43	36	1.48	46	-240	-300	-360	334,500	1.23
20	40	0	-40	310	1.24	47	-93	-200	-200	530	0.81
21	35	0	-35	28,900	0.70	48	-97	-200	-200	3,280	0.69
22	32	0	-32	192,000	0.77	49	-100	-200	-200	7,120	1.10
23	0	-46	-92	660	1.66	50	-103	-200	-200	21,250	1.28
24	0	-43	-86	2,730	2.20	51	-180	-300	-300	330	0.76
25	0	-40	-81	22,700	1.39	52	-184	-300	-300	1,560	0.82
26	0	-37	-75	189,000	0.91	53	-188	-300	-300	4,950	1.30
27	0	-34	-69	945,000	1.10	54	-192	-300	-300	24,700	1.31

studies are necessary to determine the form and dimensions of the limiting resistance surface. In order to achieve this, it is sufficient to add to the tests shown in Fig.3 a number of tests in tension and torsion under different hydrostatic pressures. The results shown in Table 1 were obtained taking into account the foregoing developments in the technique and methods of longevity studies in the three-dimensional stress state.

Here (Table 1) the first seven trajectories correspond to the period of failure of 8 sec obtained in uniaxial (1), one-and-a-half (2) and biaxial (3) tension torsion (4), uniaxial (5), one-and-a-half (6) and biaxial (7) compression. These seven trajectories are sufficient for establishment of the form and dimensions of the curve of limiting resistance, in the plane of two main stresses (Fig.5). As a result of isotropy we have 12 points. Trajectories 8-10 and 11-13 are obtained, respectively, for torsion and tension under pressures of 100, 200 and 300 MPa. The data correspond to the three-dimensional stress state, they cannot be represented in Fig.5. Trajectories 14-18, 19-22 and 23-27 and their periods of fracture were obtained, respectively, in one-and-a-half ($\sigma_1=2\sigma_2$) tension, torsion and one-and-a-half ($\sigma_2=2\sigma_3$) compression. As these results in time are obtained in an unchanged stress state, we can represent them as the curves of longevity (Fig.6). In order to compare the results, the stress state is expressed via parameter I. The considered 27 experiments are, in principle, sufficient for constructing of a phenomenological model, adequately predicting the longevity in an arbitrary stress state, as we have the information describing the influence of the stress state type and time on longevity. Other trajectories (28-54) were obtained at more simple deformations (Fig.2a, b, c) using higher pressures.

It should be mentioned that criteria of static and long-term strength must be in a definite correlation; in particular, the mathematical model of long strength criteria, being the most general, has to degenerate at fixed periods into the reliable static strength criterion. In this sense, it is possible to give as an example the Zhurkov formula for longevity criterion

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma\delta}{RT}\right) \quad (6)$$

This criterion at a fixed time, e.g. 10 s, gives $\delta = [U_0 - \log(\tau/\tau_0)RT]/\gamma = \text{const}$, which corresponds to the first theory of strength. Taking into account that the first theory is absolutely not supported by experiment neither for brittle nor for plastic materials for an arbitrary stress state in quasistatic conditions, consequently, one cannot anticipate agreement with experimental data in different stress state types for longevity.

Among many static strength criteria, the Kan-Pervushin criterion [11] is in good agreement with the experimental data and, via coordinates I and L it is represented as follows

$$I + BL + CL^2 = A. \quad (7)$$

In the form (7) for the three-dimensional stress state, the Kan-Pervushin criterion

represents a rotational paraboloid relative to the hydrostatic axis. If in the exponent in (6) we replace the stress by the left side of criterion (7), we obtain the mathematical model in the form

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma I - \alpha L - \beta L^2}{RT}\right), \quad (8)$$

which well describes longevity in every stress state. Here τ_0 - pre-exponential factor; U_0 - activation energy; γ - structure-sensitive factor (with the dimension of volume m^3/μ and taking into account the failure of the polymer under the action of shear deformation); α - structure-sensitive factor (m^3/μ , taking into account the failure of the polymer under the action of shear deformation); β - structure-sensitive factor ($\text{m}^6/\text{kJ}\cdot\mu$); R - gas constant; T - temperature.

In order to define the constants in (8), let us rewrite it in the form

$$\log(\tau/\tau_0)RT = U_0 - \gamma I - \alpha L - \beta L^2 \quad (9)$$

From (9) it follows that in order to predict the longevity in an arbitrary stress state, one has to determine only five constants (U_0 , γ , α , β and τ_0) which requires only five experiments. However, the situation concerning determination of the constants is actually somewhat more complicated, because from five experiments it is not possible to establish the form and dimensions of the family of isochronic failure surfaces and, consequently, the number of experiments must be sufficient to provide such a possibility. From (9) it follows that in order to determine the first four constants it is not necessary to carry out studies on a long-term base and they can be determined practically by static testing. The pre-exponential factor τ_0 can be established, if experimental data are available on longevity not only for different stress state types but also with varying temperature (which we do not have). Therefore, the value of this constant was assumed to be equal to its universal value ($\tau_0 = 10^{-13}$ s) /4/.

Four constant coefficients in criterion (8) were determined by solving the overfilled system of equations of the (9) type by the least squares method, using the experimental data given in Table 1. The constants found by this method are: $U_0 = 155$ kJ/ μ ; $\gamma = 11.9$ m^3/μ ; $\alpha = 16.9 \cdot 10^{-5}$ m^3/μ ; $\beta = 14.0 \cdot 10^{11}$ $\text{m}^6/\text{kJ}\cdot\mu$. The standard deviation for 54 averaged failure periods was 13.9%. Comparison of the theoretical fracture period τ_T , calculated according to (8) using the obtained constants, with the experimental period τ_E for all types of stress state (in the form of the ratio τ_T/τ_E) is given in Table 1. The standard deviation 14% means that the isochronic surfaces of longevity are the rotational surfaces relative to the hydrostatic axis, because criterion (8) at a fixed time represents a rotational paraboloid relative to coordinate L .

The graphic illustration of the agreement of experimental longevity data in a three-dimensional stress state is shown in Figs. 5-7. Theoretical isochronic curves

for periods equal to 8 (1), $8 \cdot 10^3$ (2) and $8 \cdot 10^6$ s (3) in the conditions of plane stress state are shown in Fig.5. In this figure, for the theoretical curve 1, experimental points are situated in all four quadrants; for all other theoretical isochronic curves it seems impossible to represent experimental values of longevity, because one cannot carry out an experiment with a predetermined fracture period. In this case, agreement between theory and experiment can be established only by statistical methods.

Fig.5. Isochronic longevity curves for epoxide resin in plane stress state and periods 8 s (1), $8 \cdot 10^3$ s (2) and $8 \cdot 10^6$ s (3). Curves are calculated according to equation (8).

The theoretical values of longevity for three types of stress state and their comparison with experiment are shown in Fig.6. Here curves 1 and 3 relate to biaxial tension and compression, respectively, when the ratio of the main stresses equals two, and the curve 2 corresponds to shear deformation. Experimental and theoretical data shown in Fig.7 illustrate the geometry of the surface of limiting resistance and how it changes for the three periods of 8 (1), $8 \cdot 10^3$ (2) and $8 \cdot 10^6$ s (3). Here the situation is analogous to the results of Fig.5, i.e. the experimental

Fig. 6. Longevity of epoxide resin in biaxial tension (1), shear (2) and biaxial compression (3). Curves are calculated according to equation (8).

Fig. 7. Isochronic longevity curves in three-dimensional stress state for periods 8 s (1), $8 \cdot 10^3$ s (2) and $8 \cdot 10^6$ s (3). Curves are calculated according to equation (8).

points may be shown only on curve 1. However, the standard deviation 14% represents a convincing evidence of the advantage of the mathematical model (8). The results obtained in the present work agree with practically all data obtained in other published work. It should only be mentioned that in earlier studies of longevity there was no success in varying different stress states within a wide range, which did not permit conclusions about the role of the stress deviator and the spherical stress tensor on the longevity of polymeric materials. Unfortunately, most of the experimental data on longevity of polymeric materials cannot be used to obtain constant coefficients in (8), because their reliable determination would require a variation of parameter L in a wider region than in the experiments on tension and torsion. In the opposite case, the system of equations for determination of constant coefficients is not well defined.

In conclusion, it is necessary to mention that the kinetic concept of fracture becomes apparent in every type of stress state. The prediction of longevity may be done according to (8), all constant coefficients included in this criterion being invariant relative to the type of stress state.

However, it should be especially underlined that the least irregularities or inaccuracies in realization of the given type of stress state, as it takes place in compression of a polymeric specimen by stiff stamps /5/, which is assumed to be uniaxial compression, introduce confusion into the strict and physically founded propositions of the kinetic theory of fracture.

The established rules of longevity of an epoxide resin in a three-dimensional stress state permit the use of available test results for construction of the mathematical model in the form (8). These data must contain at least experimental data on uniaxial and biaxial equal tension and torsion at different hydrostatic pressures.

It was interesting to establish to what extent the metal longevity corresponds

Table 2. Analysis of reliability of longevity criteria.

Material	Constant coefficients				Error Δ , %
	U_0 , kJ/ μ	γ , kJ/ $\mu \cdot \text{MPa}$	α , kJ/ $\mu \cdot \text{MPa}$	β , kJ/ $\mu \cdot (\text{MPa})^2$	
Zinc	126	0.79	0.071	$7.5 \cdot 10^{-5}$	6
	122	0.79	0.007	-	28
	121	0.71	-	-	231
Aluminium	211	0.80	0.027	$7.1 \cdot 10^{-5}$	14
	200	0.75	0.013	-	135
	160	0.43	-	-	4,000
Silver	267	0.75	0.029	$6.3 \cdot 10^{-5}$	11
	263	0.75	0.022	-	16
	239	0.63	-	-	363

to the criterion (8). With that end in view, data on longevity of zinc, aluminium and silver, obtained in tensile experiments in a high pressure vessel were used /13/. The authors of /13/ treated their experimental data with the help of the Zhurkov formula, assuming that U_0 and γ are some functions of pressure, which in general strongly contradicts the physical representation of the process. In particular it is incomprehensible why the activation energy should depend on pressure and the coefficient γ on the type of stress state. The longevity criterion in the form (8) also removes the contradiction in dimensions in the Zhurkov formula, and three coefficients are invariants independent of the type of stress state. Four constants in (8) were found by solving the overfilled system of equations of the (9) type by the least squares method, varying the number of coefficients in the exponent. If $\alpha=\beta=0$, (8) reduces to Zhurkov's formula, which unsatisfactorily describes longevity in tension, as the error reaches 4,000% (four thousand percent) for aluminium. Every criterion of longevity at fixed times, e.g. $\tau=1$ min, must degenerate into the adjustable static strength criterion. Zhurkov's formula degenerates into the first theory for a three-dimensional stress state, not being supported by experiment and, naturally, neither does the longevity theory agree with experiment. Criterion (8) at a fixed time degenerates into the Kan-Pervushin theory, being well conformed both in static and longevity aspects of strength (errors in the table 6, 14 and 11%).

A quantitative estimation of the reliability of the model (8) was carried out using experimental data obtained by other investigators /14-16/ for three kinds of steel (Table 3). The analysis of the most detailed data /16/ showed that the error for the steel 12X18H10T according to (8) is 34.8% for the best criterion of longevity, from the point of view of the authors /16/, of the type

$$\tau = C \sigma_{\text{equiv}}^{-m} \quad (10)$$

The errors for the equivalent stress τ_{max} , σ_1 and $2\tau_{\text{max}}$, respectively, are 37, 48 and 44%. However, it is necessary to mention here that in spite of the fact that the study in /16/ was carried out on 24 independent trajectories, these data

Table 3. Constant coefficient of longevity criteria.

Type of steel*	316L	321	304
Temperature, K	843	883	1,123
U_0 , kJ/ μ	358	370	417
γ , m3/ μ	0.23	0.30	0.062
α , m3/ μ	0.065	0.069	0.021
Δ , % according to (8)	24.1	25.6	34.9
C, s	$1.06 \cdot 10^{14}$	$1.36 \cdot 10^{16}$	$1.97 \cdot 10^{12}$
m	3.39	4.67	2.74
Δ , % according to (10)	64.2	97.5	43.7

* Analogs according to: Enduro stainless steel. Republic Steel Corp. 1972.

provided little information because parameter l varied in a narrow range; besides, the chosen trajectories were situated very close to one another. Consequently, when loading a thin-walled tubular specimen with internal pressure, axial force and torsion it seems impossible to obtain the minimum information permitting reliable identification of longevity criteria. For this reason, as in coordinates R and L the experimental data are situated in a rather narrow range of variation of parameter L , any criteria are valid for their description, including those based on the first theory.

By the statistical treatment of longevity data for steels 15X1M1F /14/ and 1X13H12T /15/, the advantage of the model (8) was established, in comparison with (10). The quantitative part of the investigations is shown in Table 3 where the constant coefficients for two theories and the errors are cited. As the experimental data were obtained in a narrow range of change in the spherical stress tensor, there is no sense to introduce the coefficient β in (8).

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