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NUMERIC MODELING OF THE STRENGTH AND LONGEVITY OF STRUCTURES WITH ALLOWANCE FOR SCALE EFFECT. REPORT 2. INVESTIGATION OF THE STRENGTH AND LONGEVITY OF HARD-ALLOY DIES FOR HIGH-PRESSURE APPARATUS

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UDC 539.893

The results of evaluation of the structural strength and longevity of a hard-alloy die of anvil-type high-pressure apparatus (HPA) with recesses intended for the synthesis of superhard materials are presented. Calculations are performed by the finite-element method (FEM) with allowance for the characteristic features of content interaction and the thermoelastoplastic stress–strain state of the basis HPA components, as well as the structural inhomogeneity of the material, which is sensitive to scale effect. Isolines of equivalent stresses in the die in accordance with the Pisarenko–Lebedev strength criterion after assembly of the HPA and in its loading regime with the effective pressure and temperature are obtained. The number of load cycles required to fail the die is established using the developed longevity criterion. The dependence of the strength and operational stability of geometrically similar dies on their effective volume, which agrees satisfactorily with experimental data, is investigated.

Using previously developed criteria [1], let us examine the characteristic features of the calculation of the static and fatigue strengths of structures in an example of the investigation of the strength and longevity of hard-alloy dies of anvil-type high-pressure apparatus with recesses [2], taking into account the characteristic features of their stress–strain state. Apparatus of this type are used to produce superhard materials as a result of phase transformations in the reaction zone subject to high pressures and temperatures.

HPA include (Fig. 1) two coaxially arranged hard-alloy dies. Recesses in the form of cones, which are coupled with a sphere, are built into the working ends of the dies, which are brought together in the loading process. A container fabricated from ore (lithographic limestone or pyrophillite) with a reaction cell containing a mixture of powders is placed in the recess of one of the dies. In producing synthetic diamonds, this may be, e.g., a mixture of graphite with metal chips and a solvent. During compression of the apparatus, the container is plastically deformed by the support plates of the press under a force of 10-20 kN, and is partially extruded from the cavity of the recess. A deformable seal, which insulates the current-carrying components, prevents further escape of container material from the high-pressure cavity and reinforces the lower and upper hard-alloy dies, is formed in this case.

The mixture in the reaction cell is heated to the synthesis temperature by passing a low-voltage current through the cell. The hard-alloy die is engaged along lateral surface CD by a block of steel rings, which are sequentially pressed one against the other and against the die with a guaranteed interference fit. During operation, the die is heated on average

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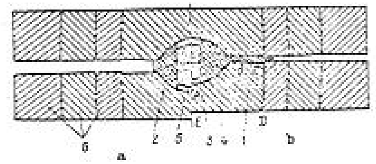


Fig. 1

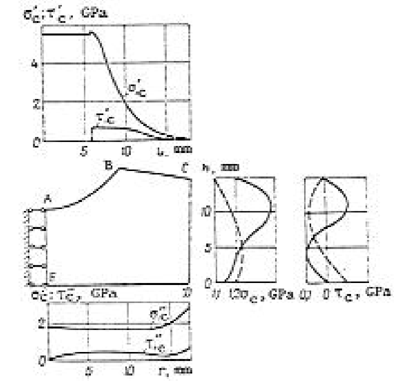


Fig. 2

Fig. 1. Schematic diagram of anvil-type high-pressure apparatus with recesses prior to (a) and after (b) compression: 1) die; 2) container; 3) reactive charge; 4) deformable seal; 5) heater; 6) reinforcing rings.

Fig. 2. Loading diagrams of hard-alloy die of HPA after its impression into ring (broken lines) and loading under working pressure (solid lines).

to a temperature of 600-800°C and maintained to failure over several hundreds of load cycles. The symmetry of the type of HPA under consideration about the vertical axis and horizontal plane of the block—die joint makes it possible for us to limit the investigations to one quarter of its axial section.

Some calculations of the thermal-stress state of HPA were performed in [3-7]. The results of evaluation of the limiting state of a hard-alloy die using the Pisarenko—Lebedev generalized static-strength criterion are presented in [4, 6]. These studies, however, contain a different kind of assumption in the formulation of the boundary conditions, which result in significant discrepancies between computed and experimental data. In this connection, let us dwell in greater detail on determination of the loads acting in the direction of the HPA components that come in contact with the die.

During service, the die is subjected to a cyclically varying load. In this case, it is possible to isolate two basic load regimes. According to the first, which is hereinafter called the compression regime, the die is loaded by normal σ_c and tangential τ_c loads that develop after assembling the HPA with negative allowance and that are equivalent to a block of reinforcing rings (Fig. 2) along lateral surface CD alone. The second form of force-induced load corresponds to the working regime, where the following act on the matrix, in addition to the increase in the coupling stresses that had been induced:

normal σ_c' and tangential τ_c' stresses governed by contact interaction with the plastically deformable lithographic-limestone container on shaped surface ABC; and,

the stresses σ_c'' and τ_c'', which are caused by contact interaction with the support plate of the press, on the flat end (surface ED).

The stress distribution in the metallic components of the HPA and on their contact boundary is obtained by the finite-element method using the algorithm and software package described previously in [8-10]. According to the algorithm, the HPA components, which are preliminarily discretized into finite elements, are considered jointly on the assumption that the contact zone is known and does not change during the course of loading. A radial negative assembly tolerance was assigned as the difference between the paired-node displacements normal to the contact surface, which have similar coordinates, but different numbering. It was assumed that the contact friction is described by Coulomb's law with a friction coefficient of 0.15 between the rings, and 0.09 between the dies and support plate. This same coefficient was assigned between the dies and the first ring of the banding unit. The elastoplastic deformations of the steel rings were taken into account in the calculations.

In connection with the fact that the contact thermoelastoplastic problem is, in the general case, nonlinear due to energy dissipation caused by plastic deformation and frictional forces on the contact surface, it was solved by iteration using the algorithm of the method of initial stresses.

It is apparent from Fig. 2 that the normal component of contact pressure increases to 1.39 GPa on the contact boundary between the die and ring unit in the operating mode. The maximum discrepancy in the stress values σ_c obtained by the FEM and in accordance with the Lamé equations given in [11], which are used in designing HPA, but disregard the actual shape and characteristic features of the contact interaction between the components of the die block, amounted to approximately 16%. Moreover, the distribution of stresses σ_c along lateral surface CD differs significantly from a uniform distribution; this implies that the FEM and the solution obtained for the contact problem by this method must be used to calculate the optimal parameters of the die-block assembly. As will be shown below, cyclic variation in the magnitude and direction of the tangential stresses τ_c exert a significant influence on the strength, and, especially, on the longevity of the die.

The distribution of the contact stresses σ_c' and τ_c' on the working surface ABC of the die during compression is established as a result of calculations performed by the method of slip lines for the limiting state of the plastically deforming container [12]. It was assumed in the calculations that the constants in the Coulomb plasticity condition, which characterizes the relationship between the shear strength of the container material and the pressure level attained, depend on the nonuniformity of the temperature field.

The related nonstationary nonlinear problem of elastical and thermal conductivity has been stated and solved by the FEM [9] to determine the temperature in HPA. The nonlinearity of the problem is dictated by the electrophysical and thermophysical properties of the materials. The extent to which the electrical and thermal conductivities are related follows from the fact that the field of internal heat sources, which, in turn, is defined only when the electrical-conductivity problem is solved, should be known to solve the thermal-conductivity problem. The electrophysical properties of the materials, which are temperature-dependent, must be assumed to solve the electrical-conductivity problem. An implicit scheme was used for a finite-difference approximation of the temperature with time. The temperature stresses were determined for each time interval and after the problem had been carried over to the stationary regime.

Consideration of the temperature dependence of the physicomechanical properties of the seal material made it possible to reduce significantly the jumps in the stresses σ_c' and τ_c' on the contact boundary between the container and the reactive mixture, and, in turn, to eliminate corresponding stress concentration on the working surface of the die [3, 4]. The stress state of the mixture, and also the seal in the region where the material's shear strength is insignificant with the condition that $\tau_c' = 0$, can be considered uniform and hydrostatic. On the σ_c' curve (Fig. 2), this is characterized by the presence of a horizontal segment corresponding to the hydrostatic pressure, which amounts to 5.5 GPa.

The distribution of the contact stresses σ_c'' and τ_c'' between the dies and the support plate of the press during effective loading of the HPA is characterized by significant nonuniformity, which increases with increasing radius of the die block (Fig. 2). As a result, the maximum stresses $\sigma_c'' = 2.6$ GPa and $\tau_c'' = 0.6$ GPa are attained in the region of point D. In the case of maximum friction (cohesion) on the contact surface, the contact stress σ_c'' increases to 3.4 GPa, and the stress τ_c'' to 1.0 GPa [13].

Thus, the calculations that we performed made it possible to define the boundary conditions more precisely, and, in turn, to improve the reliability of the results of subsequent investigations of the stress—strain and limiting states of the basic components of HPA.

The distribution of the components of the stress tensors σ_1 and σ_2 in a hard-alloy die, which corresponds to the two schemes under consideration for the thermal-force loading of HPA, is shown in Figs. 3 and 4. It is apparent that where after assembly, the maximum radial σ_r and tangential σ_θ stresses of −2.4 GPa are obtained at the same point in the cavity of the recess, they are carried out onto the cone-shape surface of the die in the operating regime. The axial stresses, which are insignificant in magnitude after embedding of the die, increase to 5 GPa in the region of point A and to 2.2 GPa on the edge of the support surface during loading. The distribution of tangential stresses τ_{rz} in the die is characterized by a change in sign on the lateral CD and working AB surfaces. On surface AB, these stresses have a local maximum amounting to 1.8 GPa.

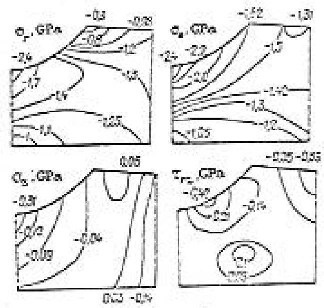


Fig. 3

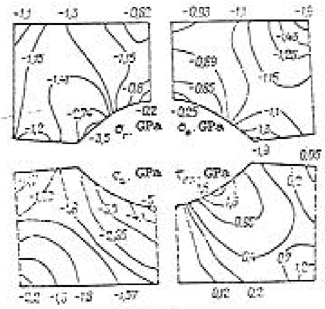


Fig. 4

Fig. 3. Distribution of components of stress tensor in axial section of die after its reinforcement with banding rings.

Fig. 4. Distribution of components of stress tensor in hard-alloy die in operating mode.

Using the components of the stress tensors σ_1 and σ_2 as initial data, let us examine the static and fatigue strength of a hard-alloy die with allowance for scale effect, and the form and uniformity of the stress–strain state [1, 9]. The Pisarenko–Lebedev criterion served as the basic criterion for evaluation of the strength of the die during its one-time loading [14]. According to experimental and theoretical data [15, 16], this criterion describes most completely the limiting state of structurally inhomogeneous brittle materials, e.g., sintered hard tungsten–cobalt alloys with very different ultimate tensile and compressive strengths [17]. The Pisarenko–Lebedev criterion in dimensionless form, where the mechanical constants depend on the loaded volume V_ℓ of the material in conformity with Weibull's statistical theory [18] is as follows:

$$\sigma_e = F(\sigma, V_\ell) = \frac{\chi(V_\ell)\sigma_i + [1-\chi(V_\ell)]\,\sigma_1 A(V_\ell)^{1-\frac{\sigma_1+\sigma_2+\sigma_3}{\sigma_i}}}{\sigma_+(V_\ell)} \leq 1. \tag{1}$$

Here: $\chi(V_\ell) = \sigma_+(V_\ell)/\sigma_-(V_\ell)$; A is a parameter of the material's structure where

$$A = \frac{\sigma_+(V_\ell) - \sqrt{3}\,\chi(V_\ell)\,\tau_{cr}(V_\ell)}{[1-\chi(V_\ell)]\,\tau_{cr}(V_\ell)};$$

$\sigma_+(V_\ell)$, $\sigma_-(V_\ell)$, and $\tau_{cr}(V_\ell)$ are the ultimate tensile, compressive, and torsional strengths of the hard alloy; σ_i is the stress intensity, and σ_ℓ (ℓ = 1, 2, 3) are the principal stresses.

The relationship between the mechanical characteristics of the material, which are introduced to the criterion, and the loaded volume is determined experimentally from tests of standard specimens [16, 17]. Representation of test results of hard-alloy specimens in tension, compression, and torsion in $\log\sigma - \log V$ coordinates makes it possible to approximate them by expressions of the form $A_i = K_i/(V_\ell^{1/m_i})$, which correspond to the Weibull theory:

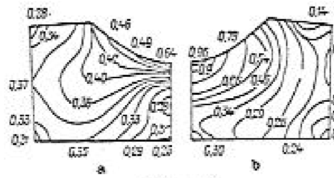
$$\sigma_+ = 0.81\,\frac{1}{V_\ell^{1/m_1}}\ \text{GPa};\quad \sigma_- = 3.36\,\frac{1}{V_\ell^{1/m_2}}\ \text{GPa};\quad \tau_{cr} = 0.75\,\frac{1}{V_\ell^{1/m_3}}\ \text{GPa},$$

where m_1 = 8.77, m_2 = 12.54, and m_3 = 8.05.

Then, $\chi = 0.24/V_\ell^{0.034}$ and $A = 0.6/V_\ell^{-0.071}$. Note that in the case of a uniform stress state (uniaxial tension, compression, etc.), the magnitude of the loaded volume agrees with the volume of the effective region of the specimen being tested.

The significance of the loaded volume in a nonuniform stress state was determined in the following manner [1]:

$$V_\ell = \int_V \left[\frac{\sigma_e(r)}{\sigma_{e\max}}\right]^{m(n)} dV, \tag{2}$$



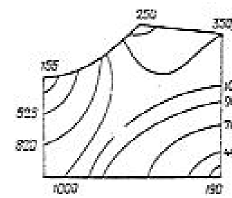


Fig. 5 Fig. 6

Fig. 5. Isolines of equivalent stresses in die in embedment and working-load regimes, obtained on basis of nonlocal criterion of static strength.

Fig. 6. Isolines of number of die-loading cycles to failure, obtained from longevity criterion.

where $\sigma_e(r)$ and σ_{emax} are the current and maximum values of the equivalent stresses calculated in accordance with criterion (1) in a volume V; r is the radius-vector of a point of the volume; $m(n)$ is a parameter of the material's homogeneity, which depends on the unit vector $n = \sigma/|\sigma|$ of vector σ, which is oriented in stress space.

Note that (2) is an equation for determination of the loaded volume V_ℓ in view of the fact that in accordance with Eq. (1), the expression under the integral depends on V_ℓ in terms of the equivalent stresses σ_e. To determine V_ℓ and $\sigma_e(r)$ from the assigned stress field $\sigma(r)$, it is therefore necessary to carry out the following simple iteration procedure.

1. Assign the initial value $V_\ell = (0.01\text{-}0.1)V$.
2. Determine the material constants $A_i(V_\ell)$ and the distribution of $\sigma_e(r)$.
3. Determine σ_{emax}.
4. Substitute $\sigma_e(r)$ in Eq. (2) and obtain the new value for V_ℓ.

Let us then repeat steps 1-3 until the difference between the last two computed values of V_ℓ are no smaller than the small value $\varepsilon = 0.01$ assigned in advance.

For large m values and significant nonuniformity of the stress field $\sigma_e(r)$, only the heavily loaded regions contribute to V_ℓ. When $m = 10$ and $\sigma_e/\sigma_{emax} = 0.7$, e.g., we have $(\sigma_e \times \sigma_{emax})^m \approx 0.03$. In components with clearly expressed stress concentrators, therefore, $V_\ell \ll V$. In this case, the allowable stresses in the region of the concentrator may be significantly higher than those in a specimen of the same volume under a uniform stress state.

The equations derived by Novikov et al. [1] for a longevity criterion, which are written for an asymmetric load cycle and a material that resists tension and compression differently, can be used to evaluate the operational stability of a die:

$$\frac{|\sigma_a|}{|\sigma_+|} = \left(1 - \frac{|\sigma_m|}{|\sigma_+|}\eta\right) Q(N_1);$$
$$\frac{|\sigma_a|}{|\sigma_-|} = \left(1 + \frac{|\sigma_m|}{|\sigma_-|}\eta\right) Q(N_2). \qquad (3)$$

The number of load cycles to failure is then defined as $N = \min(N_1, N_2)$ after substituting the ultimate strengths σ_+ and σ_- of the material, and the amplitude σ_a and mean σ_m stresses of the cycle, as well as the functional relationship Q(N) in Eq. (3). If the tensors σ_1 and σ_2 correspond to the loaded state at any one point of the volume of the die after assembly and in the operating mode, σ_a and σ_m are defined as:

$$\sigma_a = \frac{\sigma_2 - \sigma_1}{2}; \quad \sigma_m = \frac{\sigma_1 + \sigma_2}{2} - \sigma_0, \qquad (4)$$

where

$$\sigma_0 = \sigma_1 - \frac{\sigma_1 (\sigma_2 - \sigma_1)}{|\sigma_2 - \sigma_1|^2} (\sigma_2 - \sigma_1) \ [1].$$

To calculate the stress vectors σ_+ and σ_-, we can represent them as

$$\sigma_+ = \lambda_+ (\sigma_1 - \sigma_0) + \sigma_0; \qquad \sigma_- = \lambda_- (\sigma_2 - \sigma_0) + \sigma_0. \tag{5}$$

To determine the scalar parameters λ_+ and λ_- of expression (5), and also the values of the material constants, the principal stresses and their intensities can be substituted in criterion (1), dropping the sign of the inequality; in this case, we obtain $F(\lambda) = 1$. After substituting the principal stresses σ_{max}, σ_{min}, and σ_θ, which are expressed in terms of the undefined parameter λ, in Eq. (1), however, it is unclear which of these stresses to use as the principal stress σ_1. Since it is known that $\sigma_{max} > \sigma_{min}$, σ_1 may be equal to σ_{max} or σ_θ alone. Let us describe the algorithm for determining σ_1 and one of the roots, for example, $\lambda = \lambda_+$ (λ_- can be determined similarly).

1. Let $\sigma_1 = \sigma_{max}$.
2. Assign the initial value $\lambda = \lambda_0 > 0$.
3. Determine $F(\lambda)$ and, solving the equation $F(\lambda) = 1$ by the method of successive approximations, we obtain the desired λ.
4. Let us calculate the stresses σ_1, σ_{max}, and σ_θ. If $\sigma_{max} \geqslant \sigma_\theta$, the computation of σ_1 and λ_+ can be considered final for the point in question. In the case where $\sigma_{max} < \sigma_\theta$, we can assume $\sigma_1 = \sigma_\theta$, and return to step 2. To determine λ_-, we can assign a rather large negative initial value to λ and proceed in a similar manner.

This sequence of operations is carried out at all points of the region. When the FEM is used as the computational apparatus, these points are the centers of gravity of the triangular elements. In the special case when $\sigma_0 = 0$, i.e., the line along which stress cycling occurs passes through the origin of coordinates [1], and the values of λ_+ and λ_- can be established in accordance with an iteration-free scheme directly from criterion (3). After this, the vectors of the material's ultimate strengths σ_+ and σ_- for each point of the region under investigation and the specific load cycle are determined, just as the values of λ_+, from Eqs. (5).

The expression for the Q(N) function can be obtained by approximating experimental data derived from fatigue tests of specimens subjected to cyclic loading. For hard tungsten–cobalt alloys tested under a harmonic cyclic load [16], e.g., the Q(N) relationship assumes the form

$$Q(N) = 1 - m_N \log N, \tag{6}$$

where m_N is a coefficient characterizing the slope of the fatigue line in a semilogarithmic coordinate system. For the hard alloys with 6, 15, and 25% of cobalt, which are used in the production of basic HPA elements, the value of m_N is equal, respectively, to 0.112, 0.103, and 0.111.

To evaluate the effectiveness of the developed algorithms and software packages, the strength and longevity of a solid hard-alloy cylinder 20 mm in diameter and 10 mm high, whose stress state is characterized by two arbitrarily selected tensors of the stresses σ_1 and σ_2, the latter being functions of the coordinates of the point of the body, were calculated as a trial problem:

$$\sigma_{r1} = 2z + 50; \quad \sigma_{z1} = -4r; \quad \sigma_{r2} = -5z + 40;$$
$$\sigma_{z2} = -4r - 40; \quad \sigma_{\theta 1} = \sigma_{\theta 2} = \tau_{rz1} = \tau_{rz2} = 0.$$

The cylinder is divided into 121 nodes and 200 triangular linear elements using an automated grid generator [19]. The results of the calculations are presented in Table 1. Note that three and four approximations were required to determine the loaded volume and material constants for the first and second stress states, respectively. The errors generated in computing the volume V_ξ for the two forms of stress state are given in the last column of the table. According to numeric calculations, the longevity of the cylinder was 3270 cycles. Considering that N = 2843 cycles for the analytic calculation, the error ϵ_N generated in calculating the longevity reached −15%. If a finer grid of 676 nodes and 1350 elements is applied to the cylinder, the error generated in calculating V_ξ for the first and second stress states is reduced to 2.41 and 5.8%, respectively. The computational error of ϵ_N is 7.45% for this grid.

Let us examine the static and fatigue strengths of a hard-alloy HPA die of the anvil type with depressions. The equivalent stresses in the die after its embedment in the ring and one-time loading under the effective pressure and temperature, which are calculated on the basis

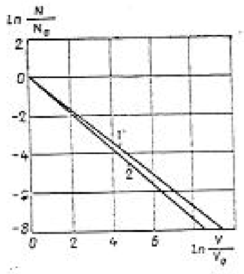


Fig. 7. Dependence of operational stability of geometrically similar dies on their volume, obtained experimentally (1) and by means of computation (2). (N_0 and V_0 are the stability and volume of the base die.)

TABLE 1. Values of Material Constants and Loaded Volume, Calculated for Test Problem

Form of stress state	σ_+, GPa	σ_-, GPa	τ_{cr}, GPa	A	χ	V_ℓ, cm^3	εV_ℓ, %
First	0,803	3.339	0.743	0,875	0.240	$\frac{1{,}080^*}{1{,}035}$	4,35
Second	0 937	3,720	0,879	0,842	0.252	$\frac{0{,}279}{0{,}241}$	15,77

*Data obtained by FEM and results of analytic computation are presented above and below the line, respectively.

of the nonlocal criterion of static strength, are shown in Fig. 5. The computed values of the loaded volume $V_{\ell 1}$ and the material constants were

$$V_{\ell 1} = 0.072\ \text{cm}^3; \quad \sigma_+ = 0.82\ \text{GPa}; \quad \sigma_- = 4.147\ \text{GPa}; \quad \tau_{cr} = 1.041\ \text{GPa}; \quad \chi = 0.284; \quad A = 0.807, \tag{7}$$

for the first stress state.

The stress state of the HPA in this regime (Fig. 5a) is characterized by a rather high degree of nonuniformity; this suggests a $V_{\ell 1}$ value that is smaller than the overall volume of the die by an order of magnitude. Analyzing the distribution of the stresses σ_e in the die, we can note that their maximum value (0.64) is obtained in the region of point A of the cavity of the recess, which falls on the axis of symmetry of the HPA and which is a structural concentrator. At another critical point on the edge of the recess, $\sigma_e = 0.42$. A somewhat lower stress σ_e (0.37) is observed on the surface CD contacting the block of rings. In the median portion of the section of the die, the stresses σ_e, as a rule, do not exceed 0.4 (Fig. 5a).

In the embedment mode when assigned assembly parameters are observed, the die exhibits a rather high factor of safety, even in the most heavily loaded regions. The contact stresses σ_c and τ_c are extremely sensitive, however, to fluctuations in negative assembly tolerances. Even a negligible deviation of the latter from the optimal may therefore lead to a pronounced increase in the contact, and, as a result, equivalent stresses. If the stresses σ_e exceed the allowable in this case, i.e., $\sigma_e > 1$, failure of the die may occur in the direction of the line connecting point A and a point belonging to contact surface DC with the maximum stress σ_e.

Let us examine the static strength of a preliminarily reinforced die loaded under the working pressure. The following values of the loaded volume $V_{\ell 2}$ and material constants are obtained as a result of the calculations:

$$V_{\ell 2} = 2.58 \cdot 10^{-3}\ \text{cm}^3; \quad \sigma_+ = 1.229\ \text{GPa}; \quad \sigma_- = 4.499\ \text{GPa}; \quad \tau_{cr} = 1.181\ \text{GPa}; \quad \chi = 0.273; \quad A = 0.781. \tag{8}$$

Comparing the data of (7) and (8), note that in the operating-load regime, the inhomogeneity of the stress state is expressed significantly more vigorously than in the embedment regime. This leads to a reduction in the reduced volume and to an increase in the strength characteristics of the die material. The calculations indicated that several elements in the region of point A of the die make the basic contribution to the volume $V_{\ell 2}$ as a result of high stress gradients.

Isolines of the equivalent stresses for the regime under investigation are presented in Fig. 5b. It is apparent that despite significant stress redistribution, the region with the maximum stresses $\sigma_e = 0.96$ is located, as before, at point A of the die recess. In this case, the stresses σ_e increased on the flat end of the die, where they amounted to 0.39 to 0.49 on the axis of symmetry of the HPA and on the edge, respectively. The increase in equivalent stresses in these regions is associated with the presence of circular bending of the die block, and also with the effect of high-level contact stresses on the side of the support plate of the press.

According to the calculations, therefore, one of the basic causes for the die being taken out of service under a one-time load may be its failure at the lower point of the cavity of the recess, where the factor of safety does not exceed 4.2%. Analysis of a large number of dies that had failed during service confirms this supposition. Failures in the form of fatigue cracking of support surface ED and local flaking of material in regions adjacent to points C and D, which are not detected as a result of strength calculations, however, are characteristic for a rather large batch of dies. Consequently, it is expedient to supplement calculations of the static strength of the die with an estimate of its longevity using fatigue-strength criterion that we developed and the appropriate software package.

The results of longevity calculations for a die in the form of isolines of the number of cycles to failure are shown in Fig. 6. It is apparent that the effective remaining life of the die is exhausted primarily in the most critical zone previously established by strength calculation, where the number of loadings N amounts to 155 cycles. In cases where there is no failure in this zone, which is possible with local hardening of the material, the extremities of the flat end of the die and the edges of recess B, where N is equal to 190 and 250 load cycles, respectively, will be the most likely failure zones.

The segments on the surface of the matrix, which are established by computational means and which sustain a limited number of load cycles, virtually coincide with the most characteristic regions of their failure during service. This is confirmed by data (obtained at the Institute of Superhard Materials, Academy of Sciences of the Ukrainian SSR and at the Poltava Artificial Diamond Plant) of statistical analysis of a large batch of dies that had been taken out of service, 50% of which had failed as cracking of the effective surface, and 25% contained radial cracks and cleavage of the material on the support surface. On the whole, however, the predicted stability of the basic hard-alloy HPA die differs from the experimentally determined stability by no more than 15%.

The dependence of the strength and operational stability of geometrically similar dies on the scalar factor when their volume is varied from 1/64 to $3V_0$ (V_0 is the volume of the base die) was investigated using the method that we developed. It is established that a more vigorous reduction in die strength is noted in the working regime with a proportional increase in their dimensions than during embedment. As the volume of the die is increased by a factor of 16, e.g., its static strength in the embedment and loading modes was reduced by 9.6 and 14.8%, respectively.

The relationship between the operational stability of geometrically similar dies and their volume in a log-log coordinate system is described by a straight line passing through zero — Fig. 7. A similar curve obtained experimentally [19] is also presented here. It is apparent that good correspondence is observed between the results of the numeric calculations and the experimental data over the entire interval of die volumes investigated. This suggests the correctness of all previously performed intermediate calculations. The analytically represented lines can be described by the equation

$$\ln \frac{N}{N_0} = -n \ln \frac{V}{V_0}, \tag{9}$$

where V_0 and N_0 are the volume and stability of the base die. The value of the coefficient n, which characterizes the slope of the line, was 1.111 for the type of dies under consideration (n = 1.065 in [20]).

It follows from Eq. (9) that the predicted operational stability of the dies depends heavily on the volume: decreasing with increasing volume. Their stability decreases by a factor of 12, e.g., with a 16-fold increase in the volume of the die.

Thus, satisfactory correspondence between the results obtained and familiar experimental data enable us to conclude that the developed method is a rather effective means of assessing the static and fatigue strength of hard-alloy components of high-pressure apparatus and can be used in calculating different types of HPA structures.

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