NUMERICAL MODELING OF THE STRENGTH AND LONGEVITY OF STRUCTURES WITH ALLOWANCE FOR SCALE EFFECT. REPORT 3. INVESTIGATION OF THE STRESS STATE, STRENGTH, AND LONGEVITY OF CYLINDRICAL-TYPE HIGH-PRESSURE APPARATUS

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UDC 539.893

The stress–strain state of one of the promising high-pressure apparatuses (HPA) after the assembly process and in the operating mode is investigated by the finite-element method. The stress state of plastically deformable container with a reactive mixture is calculated, and the effect of contact interaction and the elastoplastic deformations of equipment components is defined more precisely. The static and fatigue strengths of hard-alloy HPA components are estimated using previously developed criteria. The dependence of the strength and longevity of geometrically similar dies and punches on their effective volume is established. An interpretation of the most characteristic forms of HPA is given on the basis of computational results, and several means of improving their designs are indicated.

In addition to anvil-type high-pressure apparatuses with recesses, which were discussed earlier [1], solid-phase apparatuses of the cylindrical "Belt," "Girdle," and other types have come into widespread use, especially abroad, for the industrial synthesis of artificial diamonds and other superhard materials [2-4]. The first information on a high-pressure apparatus of this type applies to the mid-1950s, when diamonds were first synthesized in the "Belt"-type HPA. Thereafter, refinement of cylindrical-type HPA structures occurred primarily in the direction of improvement in their operational reliability, an increase in the effective volume (1000 cm^3 has been attained [5]), and the time required for the continuous-synthesis process, which consumes tens of hours at the present time. In addition to this, use of prehardened hard tungsten–cobalt alloys in combination with an effective multicomponent support of the most heavily loaded HPA has resulted in the fact that the operational stability of their best specimens has been brought to 1000 and more sinterings under a pressure and temperature of 4.5-5.5 GPa and more than 1600°C, respectively, in the reaction zone.

As practice of recent years has indicated [6-8], the search for optimal designs and the number of experimental HPA tests have been reduced considerably by numeric modeling of their stress–strain and limiting states, which correspond to the different processes of static and cyclic loading.

One of the most promising laboratory cylindrical-type HPA specimens [9], a simplified diagram of which is shown in Fig. 1, is discussed in the present report. The apparatus contains a die with a through hole and two punches, which are reinforced by multilayer blocks of steel rings, as well as a container with a reactive mixture and gasket that prevents the premature scatter of material in the reaction cell in the initial period of compression. After the HPA has been compressed between the support plates of the press, the basic components occupy the position shown in Fig. 1b. Deformable seal ABCD, which is formed from the extruding portion of the container material, fulfills primarily the same function as that in HP with anvils. Owing to an angular positioning to the direction of displacement of the punches it provides the latter with a significantly greater compressive run for the same force exerte by the press. The die and punches are usually fabricated from grade VK hard alloy (more rarely from tool alloy steel), the reinforcing rings from hardened carbon steel, and the container from pyrophillite.

Since cylindrical surface DE, which takes up the entire effective pressure during operation, e.ists in the die, significant tensile tangential stresses develop on this surface.

Institute of Superhard Materials, Academy of Sciences of the Ukrainian SSR. Translated from Problemy Prochnosti, No. 6, pp. 35-42, June, 1991. Original article submitted October 3, 1990

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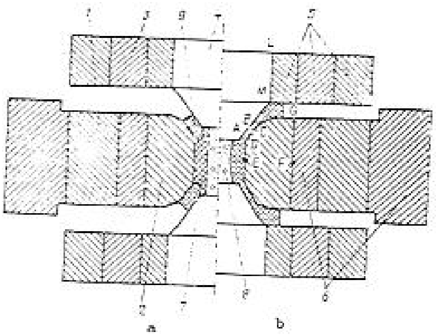


Fig. 1

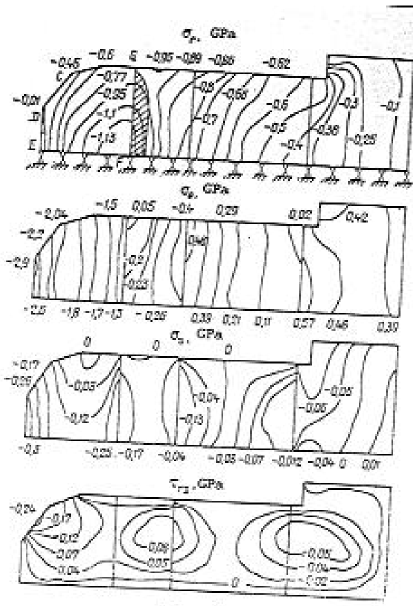


Fig. 2

Fig. 1. Schematic diagram of cylindrical-type high-pressure apparatus prior to (a) and after (b) compression: 1) die-block; 2) die; 3) punch-block; 4) punch; 5, 6) reinforcing rings; 7) container; 8) reactive mixture; 9) gasket.

Fig. 2. Computational diagram of problem and distribution of stress-tensor components in die block of HPA after its assembly with negative tolerance. (Zone of plastic deformations is hatched.)

Coupling stresses higher than those generated in HPA with anvils are required to offset these stresses. This makes it necessary to change the order of the HPA assembly, according to which the die is initially pressed into the internal ring, and the block produced in this manner is subsequently reinforced with the remaining banding rings.

The basic structural assemblies and components of a cylindrical-type HPA, being a die block or punch with steel reinforcing rings, can be represented by a system of elastoplastic bodies that come in contact with one another. According to the procedure of the finite-element method (FEM), the die block was divided into 1740 triangular linear elements connected to one another by 1023 nodes to model the stress–strain state. Following the algorithm adopted [10], neighboring assemblies, the difference in the normal displacements of which were given as the initial negative tolerance, were isolated in pairs for each of the three contact surfaces formed by the components of the die block. The problem was solved in three steps with allowance for the sequence of die-block assembly, and also the nonlinearity caused by contact interaction with plastic deformations of the banding rings.

The computational scheme of the problem, where, as we had done earlier [1], one-quarter of the axial section of the HPA was the region examined, and also the distribution of components of the tensor of stresses in the die block of the HPA after its assembly with negative tolerance are shown in Fig. 2. The zone of plastic deformations that develop in the first ring, where the tangential stresses are everywhere compressive, whereas the remaining rings operate in this regime in tension, are also shown here. The preliminarily compressive stresses σ_θ amount to 2.9 GPa on the inner surface of the die, and as will be indicated below, cannot be increased due to the limited strength of the hard-alloy die.

The results of FEM calculations for the radial stresses on the contact boundary between the die and block of rings are of practical interest primarily for their comparison with data

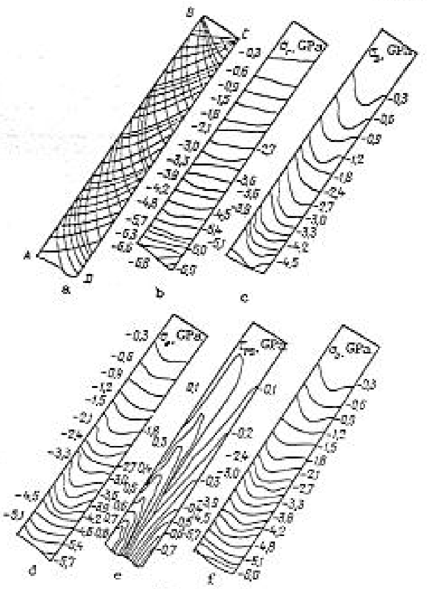


Fig. 3

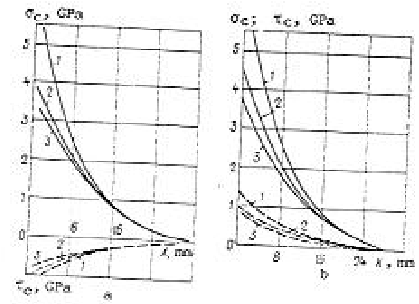


Fig. 4

Fig. 3. Fields of slip lines in seal (a), distribution of components of stress tensor (b–e) and hydrostatic pressure σ_0 (f) in plastically deformable pyrophillite container.

Fig. 4. Distribution of contact normal σ_c (solid lines) and tangential τ_c (broken lines) stresses on cone-shape surfaces of die (a) and punch (b) for different thicknesses z_1 of deformable seal: 1) $z_1 = 4.0$ mm; 2) $z_1 = 4.5$ mm; 3) $z_1 = 5.0$ mm.

obtained in accordance with Lamés approximate equation, which has been used to date in designing HPA [1]. The greatest difference (~20%) between the computational results for the stresses σ_r, which are coupling stresses for the die, is obtained at points G and F, belonging to the contact surface and the horizontal plane of symmetry. Since the coupling stresses calculated in accordance with the Lamé stresses are on the high side, they must be defined more precisely by FEM calculations to ensure the strength of the die.

The distribution of the normal and tangential stresses on the contact surface between the die and reaction container, which is used as boundary conditions, should be found to define the stress–strain state of the die block in the working mode. This distribution was established by calculating the stress state of the plastically deformable seal included between cone-shape surfaces CD and AB of the die and punch, by the method of slip lines [12] (Fig. 1). It was assumed that the physicomechanical properties of the container material depend on the temperature and pressure levels attained in the HPA. According to experimental data, the thickness of the deformed seal is 4.5 mm in the absence of punch eccentricity. In solving the problem, we assumed that surface BC is stress-free and maximum friction is possible on contact surfaces AB and CD in view of the small thickness of the seal.

The fields of slip lines in the seal, and also the distribution of the components of the stress tensor and the hydrostatic pressure $\sigma_0 = (\sigma_r + \sigma_z + \sigma_\theta)/3$ in the pyrophillite container are shown in Fig. 3. The distribution of contact normal σ_c and tangential τ_c stresses on effective surfaces AB and CD of the punch and matrix is shown in Fig. 4. The distribution of σ_c and τ_c corresponding to the case of maximum possible noncoaxiality of the basic HPA components, which amounts to 0.5 mm, is also presented here. Axis X is directed along the generatrix of cone AB for the punch and along line DC for the die.

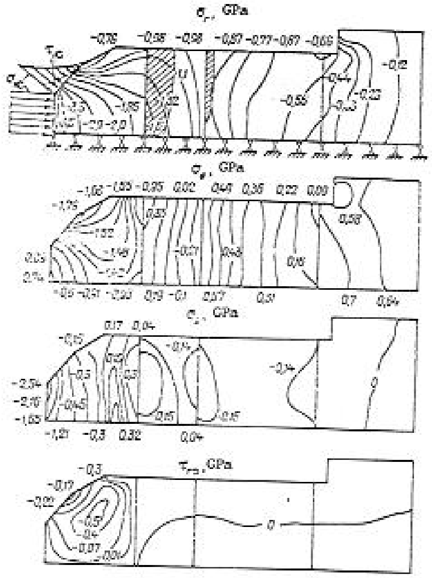


Fig. 5

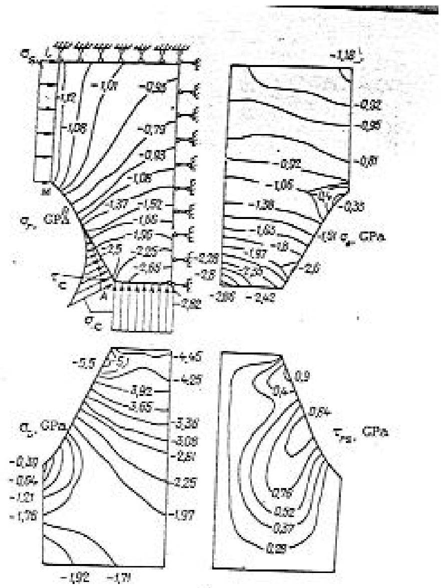


Fig. 6

Fig. 5. Computational scheme and distribution of components of tensor of stresses in HPA die block in operating mode. (Zones of plastic deformations are hatched.)

Fig. 6. Computational scheme and distribution of components of tensor of stresses in high-alloy punch in operating mode.

It is apparent from Fig. 4 that a one-sided decrease in the thickness of the seal to $z_1 = 4.0$ mm leads to a significant increase in contact pressures as compared with those for the symmetric case. At point D on the surface of the die, for example, the stresses σ_c increase from 4.5 to 6.5 GPa, and τ_c to 1.5 GPa. The stresses σ_c are distributed similarly on contact surface AB of the punch, while the tangential stresses τ_c change to the opposite sign.

The computational scheme of the die block, which corresponds to the type of stress under consideration in the absence of punch eccentricity, is shown in Fig. 5. Here, the assumption is made (it has experimental confirmation) that in the effective zone of the HPA, a hydrostatic stress state is realized in the synthesis process. When $\tau_c = 0$, this dictates the assignment of uniformly distributed contact stresses $\sigma_c = 4.5$ GPa on the cylindrical surface of the die in formulating the edge problem.

Analyzing the distribution of coordinate stresses (Fig. 5), note that despite a 22% increase in coupling pressures from the side of the block they cannot completely compensate for the tensile stresses σ_θ, which amount to 0.74 GPa in the region of point E of the effective surface of the die. Maximum values of the stresses σ_r and σ_z, which are 4.5 and 2.54 GPa, respectively, are attained on this same surface. The zone of plastic deformations in the first ring occupies approximately one-third of the volume, while it is manifested in a rather narrow layer near the contact in the second ring.

If we assume that the die is made of a hardened tool steel, as calculations performed by Shestakov et al. [8] indicate, the presence of a zone of plastic deformation, which forms in the region of cylindrical surface ED under a working pressure of 3.2 GPa, results in significant stress redistribution. As a result, compressive stresses σ_θ = 0.84 GPa occur on the inner surface of the steel die in contrast to the hard-alloy die. Under a pressure 4.5 GPa in the HPA, the plastic deformation of the indicated surface amounts to 2.5%, while the diameter of the through hole in the die is increased by 0.84 mm. Under a pressure of more than

TABLE 1. Values of Mechanical Constants and Loaded Volume of Hard Alloy VK6, Obtained for Different Forms of Stress State of Basic Components of Cylindrical-Type HPA

Form of stress state	HPA component	Loaded volume $V_ξ$, cm^3	Mechanical properties of hard alloy				
			σ_{t}, GPa	σ_{c}, GPa	τ_{cr}, GPa	A	χ
Pressing of reinforcing rings into block	die	31,97	0,55	2,55	0,49	0,95	0,216
	punch	13,85	0,61	2,72	0,55	0,93	0,223
Loading under working pressure	die	15,89	0,59	2,70	0,53	0,94	0,219
	punch	2,28	0,74	3,16	0,69	0,87	0,235

4.5 GPa, moreover, the first plastic deformations develop in the region of point F. In this case, the formation of a plastic hinge in the plane passing through points E and F, or fulfillment of the condition $q \leq [q]$, where q and [q] are the current and limiting values of the Odequist parameter, which characterizes the level of accumulated plastic deformation of the material, is adopted as the failure criterion [8].

Let us examine the results of calculations of the stress state of a hard-alloy punch under operating loads. The distribution of the contact stresses σ_c and τ_c for the symmetric case of the arrangement of the die and punch were used as operating loads (Fig. 4). Note that the contact problem was not solved to determine the supporting stresses σ_s on lateral surface LM of the punch (Fig. 1), which are equivalent to the effect of the block of reinforcing rings. This is associated with the fact that the shape of the components being mated is nearly cylindrical and the numeric solution does not offer advantages over results obtained from Lamé equations in this case. Analysis of the stress state suggests that it operates under nonuniform compression from all sides (Fig. 6). As is apparent from Fig. 6, all coordinate stresses, with the exception of the tangential, are maximum on the effective face, or in the local region adjacent to it in this case.

Before proceeding to analysis of the limit state of the basic HPA components after assembly and in the operating mode, let us cite data on the loaded volume and the mechanical constants of the material, which depend on the loaded volume and the form of the stress state and which are introduced in the static-strength criterion [13, 14] (Table 1). Let us note additionally that the total volumes of the die and punch are 891.6 and 297.4 cm^3, respectively.

Isolines of the equivalent stresses obtained with allowance for scale effect in a die and punch for their operating regimes under consideration are shown in Fig. 7. It is apparent that the maximum equivalent stresses σ_e in the die after assembly (Fig. 7a) occur on the surface of contact with the banding block, and also on the internal cylindrical surface, where they range from 0.7 at point E to 0.83 in the vicinity of point D. The presence of several zones with a high pressure σ_e in the die after assembly of the HPA is dictated primarily by the relatively minor inhomogeneity of the stress state and the rather high value of the loaded volume $V_ξ$ (31.97 cm^3).

In the operating mode (Fig. 7b), inhomogeneity of the stress–strain state increases significantly in the die; this is more apparent as a twofold reduction in the loaded volume ($V_ξ$ = 15.89 cm^3), and, consequently, as an increase in the strength characteristics of the hard alloy (Table 1). As a result, the level of equivalent stresses was reduced to 0.73 on surface ED, and to 0.58 in the vicinity of point C. In this case, however, the stresses σ_e at point F increased to 0.98, attaining a value that is virtually limiting for the material in question in this manner.

Analysis of the limiting state of the punch after assembly indicates that it is characterized by the presence of maximum equivalent stresses in the cylindrical portion, where according to calculations, there is an almost twofold factor of safety (σ_e = 0.55). In the working-load regime, the region of action of maximum stresses σ_e = 0.73 is found, as before, in the body of the punch, but is displaced along the axis of symmetry closer to its effective face. It is obvious that the level of stresses σ_e calculated on the basis of the static-

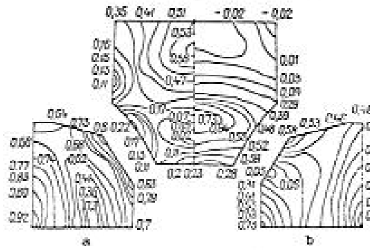
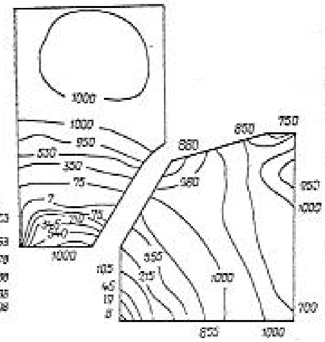


Fig. 7



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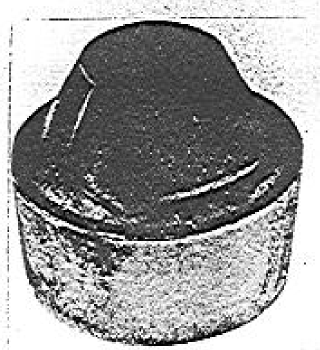

Fig. 9

Fig. 7. Distribution of equivalent stresses in die and punch of HPA after assembly (a) and in operating mode (b).

Fig. 8. Isolines of number of load cycles to failure for die and punch.

Fig. 9. Most characteristic form of failure of hard-alloy punch after several load cycles.

strength criterion is not high enough to cause failure of the punch during its one-time loading. This makes it possible to propose that punch failure, which is frequently encountered in practice after several load cycles, occurs primarily due to exhaustion of the material's fatigue strength. Calculations based on the longevity criterion confirmed this hypothesis (Fig. 8).

It is apparent from Fig. 8 that the isoline corresponding to the minimum number of load cycles, which is equal to seven, begins on the effective face of the punch, and then proceeds parallel to its axis of symmetry and base. In the process of cyclic loading of HPA, the fatigue crack that develops on the effective face of the punch has a propagation trajectory that is primarily the same or close to it. In this case, failure of the punch is combined in nature. Initiation of the crack, which grows to a certain size, causing failure, which is terminated by brittle fracture with subsequent separation of coarse segments of the hard alloy (Fig. 9), first occurs as a result of low-cycle fatigue on the effective face of the punch. The influence exerted by bending of the die on the character of its failure in the case of eccentricity is expressed in the curvature of the crack front and its displacement with respect to the axis of symmetry.

According to calculations, the number of load cycles to failure of the hard-alloy die is also low — no more than eight in the vicinity of point E. If failure does not occur at this point due to possible local hardening of the material under high hydrostatic pressure or other imprecisely defined factors, the regions adjacent to points C and D, which lie on the internal effective surface of the die, where N is 150 and 215 load cycles, respectively, become the next most critical regions. The results of the calculations are in good correspondence with data derived from laboratory tests with respect to both predicted stability, and the character of die failure, which occurs primarily as a result of the appearance and development of radial cracks, and also by delamination of the material in the horizontal plane of symmetry.

To account for the effect of the scale factor, we investigated the strength and longevity of geometrically similar dies and punches by varying their volume V from 1/16 to $5V_0$. The volume of the base components of cylindrical-type HPA were used as V_0.

The relationship between the strength and volume of the HPA elements under consideration in the log-log coordinates $\ln \sigma_e^0/\sigma_e - \ln V/V_0$ is described by straight lines (Fig. 10).

It is apparent from Fig. 10 that both in the assembly mode, and during operation of HPA, the strength of their basic components decreases with increasing effective volume; in this case, it is more striking in the loading mode than during impression. Thus, the strength of the die and punch decreased by 18.1 and 23.5%, respectively, in the operating mode as their

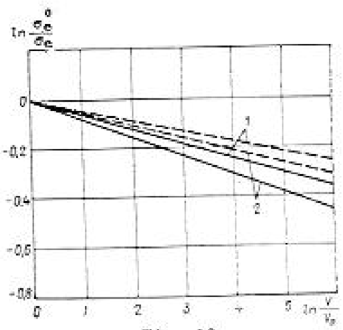

Fig. 10

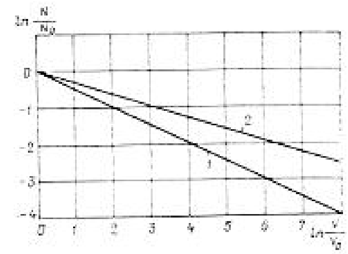

Fig. 11

Fig. 10. Relationship between static strength of geometrically similar punches (1) and dies (2) and their volume after assembly (broken lines) and loading under working pressure (solid lines). (σ_e^0 and V_0 are the strength and volume of the base dies and punch.)

Fig. 11. Relationship between operating stability of geometrically similar punches (1) and dies (2) and their volume. (N_0 and V_0 are the longevity and volume of the base dies and punch.)

volumes were increased by a factor of 16, whereas it diminished by 13.1 and 15.6% during impression. The critical volume of the die for which the limiting state ($\sigma_e = 1$) is attained in the vicinity of point E is $V = 1.38V_0$. For a proportional increase in the geometric dimensions of the punch, its strength under a one-time load is zero for a volume $V = 4.12V_0$.

The relationship between the operational stability of HPA components and their volume, which can be described in the log – log coordinate system $\ln V/V_0 - \ln N/N_0$ by straight lines that pass through zero, is shown in Fig. 11. It is apparent that during impression, the longevity of the punch decreases more vigorously with increasing volume of the HPA components, while the opposite law is observed for a one-time effective load (Fig. 10). It also follows from these diagrams that the stability of punch and die diminish by factors of 2.4 and 4, respectively, as the volume is increased by a factor of 16.

As compared with dies of anvil-type with recesses, the operating stability of which is reckoned in several hundreds of pressing-sintering cycles [13], the longevity of hard-alloy components of cylindrical-type HPA of the design under consideration is rather low — less than tens of cycles. The low stability of the hard-alloy HPA components is dictated by a characteristic feature of their structures, which contains surfaces on which the total effective pressure, which is insufficiently compensated by lateral support, acts during operation. In the die, this is the internal cylindrical surface, which according to the calculations that we performed and experimental data, is primarily subject to failure.

To increase the strength of the internal cylindrical surface, it is possible to recommend procedural methods for bulk and surface hardening [15-17], which were previously successfully tested on anvil-type HPA designs with recesses and which make it possible to develop preliminarily compressive stresses of the required magnitude. As the calculations indicated, an increase in operating stability can also be achieved as a result of structural alterations, eliminating, e.g., the stress risers at points D and E (Fig. 1) by replacing the cylindrical surface of the die with a cone-shape surface. This replacement results in the fact that during operation, it is not the total effective pressure that acts on the die in the radial direction, but its component, which is equal to the product of this pressure and the cosine of the angle between the generatrix of the cone and the vertical axis of symmetry. Note that the construction of a hard-alloy die, which is similar in shape, has been successfully employed abroad in individual modifications of "Belt"-type HPA [8].

As applies to the punch, basic structural solutions and production procedures should be directed toward the prevention of cracks on the effective face, which develop as a result of its insufficient support, especially when the pressure in the working cavity exceeds the pressure in the deformable seal or eccentricity exists for the punch. For this purpose, it is possible to recommend the construction of a composite punch in which its basic portion is made of the hard alloy VK6, and the tip of a stronger alloy of the VK5 type or diamond [19].

Let us also point out the necessity of a cautious approach toward selection of the material for the basic components of cylindrical-type HPA, since the geometric parameters and effective volume of the dies and punch significantly exceed those of dies with a recess; they therefore experience the influence exerted by scale effect, and the form and inhomogeneity of the stress—strain state to a large degree. One can be convinced of this by comparing data on the mechanical properties of the materials, which are cited above in Table 1 and in [1]. Owing to the rather large loaded volume, all basic strength characteristics of hard alloy VK6 for components of cylindrical-type HPA are significantly lower than those for the recessed die. For example, the ultimate tensile and compressive strengths of the hard alloy for the two indicated types of HPA differ by more than 2 and 1.5 times, respectively. As we know [15], however, the probability of finding crack- and pore-type defects of critical size in the components, which have a tendency for further growth, especially under a cyclic load, increases with increasing size of components fabricated from structurally inhomogeneous materials. One means of improving the longevity of cylindrical-type HPA, therefore, is to produce a virtually defect-free structure in the hard alloy as a result, e.g., of its repressing in a gas-filled constant temperature cabinet.

Let us note in conclusion that the proposed criteria, methods, and software packages are used at the present time to investigate the strength and longevity not only of high-alloy HPA components, but also other no less complex objects operating under static and cyclic loads. Calculations using isoparametric finite elements of deforming broaches of complex shape for machining internal holes in cylindrical components, and also HPA with diamond anvils intended for physical investigations in the megabar range of working pressures may serve as an example [20].

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CURVILINEAR CRACK DEVELOPMENT TRAJECTORY IN ALUMINUM ALLOYS WITH BIAXIAL CYCLIC LOADING

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UDC 539.385

A calculation and experimental study is provided for development of curvilinear cracks of different original orientation with uniaxial and biaxial tension. A marked dependence is noted for crack growth trajectory on the form of stressed state and aluminum alloy properties. It is established that the criterion considered for crack growth direction cannot be recommended as universal for a whole number of test materials. A method suggested previously for plotting calculation and experimental crack growth trajectories with a complex stressed state may be used in determining cyclic resistance characteristics for mixed forms of failure.

In the stage of crack development apart from natural study of cyclic crack resistance characteristics an important component of predicting the endurance of structural elements is determination of crack propagation trajectory. This task is particularly important for the airframe components of flying equipment which are under conditions of biaxial cyclic loading of different intensity. Here nonconformity of the directions of stress operation with the plane of orientation of possible defects is in practice the rule rather than an exception.

A model of this situation is a plate weakened by an internal through rectilinear crack which is under conditions of a general plane stressed state or plane strain (Fig. 1). A number of works are known devoted both to determining the direction of crack development in relation to the angle of its original orientation [1, 2], and to calculating crack growth trajectory with uniaxial and biaxial loading [3-13]. However, the results obtained in them do not reflect the features of properties even within the scope of a single class of materials having approximately the same elastic characteristics.

A study of the effect of aluminum alloy properties and the form of stressed state on crack growth trajectory with cyclic loading is the subject of the present work. We shall

Kazan Physicotechnical Institute, Academy of Sciences of the USSR. Translated from Problemy Prochnosti, No. 6, pp. 42-47, June, 1991. Original article submitted July 2, 1990.

 0039-2316/91/2306-0652$12.50