SIMULATION OF STRESS-DEFORMED STATES OF APPARATUS FOR HIGH PRESSURE SINTERING OF NANOMATERIALS

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Abstract. Calculation of stress-deformed states of high pressure apparatus (HPA) of “anvils with recesses” type for sintering of nanomaterials is realized by finite element analysis (FEA). At first three general regimes of HPA: “assembly”, “loading” and “unloading” are considered together. It is shown, that in certain zones of HPA hard alloy anvils arisen stresses as a result of pressure difference in the interior and from the outside of the apparatus are higher at the apparatus unloading than at the apparatus loading. At loading and unloading of HPA tensile stresses riches the maximal values at the edge of trapezoidal recess bottom of anvil. At this place the destruction probability is high. At the “assembly” regime these places are underwent under compressive stresses affect. It is obtained, that the real picture of anvil destruction during a working process of the HPA and the character of stress distribution in anvil volume calculated by us are sufficiently good conformed with each other.

1. INTRODUCTION

High pressure sintering is widely used for production of superhard materials based on high melted point compositions [1]. It allows produce highly dense nanostructed materials with increased physico-mechanical properties [2]. As a rule, a high pressure apparatus (HPA) of “anvil with recess” type are applied for these purposes in countries of CIS [3]. Various constructions of such apparatus distinguishing by the profile of working surface of anvil and the geometric dimensions are used to solve particular problems. Anvil is the most loaded element of such HPA determining the efficiency of its working and service time. Its longevity depends on safety margin caused by the characteristics of material, the value and the character of applied outer loading and the construction of anvil. Usually it is produced from WC - 6% Co hard alloy providing the longer resource of working than steel. The value and the character of applied loading, the stress distribution in anvil volume are determined by its construction and the sintering regimes – the pressure, the temperature and the character of their time changing. Increasing a service time of the HPA is obtained by providing evenness of stress distribution in anvil volume due to optimization of its construction.

Nowadays application of widely extended finite element analysis (FEA) is convenience to estimate a stress-deformed state of HPA anvil [4]. It allows to calculate sufficiently quickly stress-deformed and limiting states of HPA elements with an admissible error without huge time spandings. Using this analysis collaborators of ISM NASU under academic N.V. Novikov’s guidance the cycle of works concerning numerical simulation of stress-deformed and limiting states of HPA elements has been carried out [5-8]. Computer simulation of non-stationary processes of heating and cooling of different HPA types during a working process is carried out [9]. Effectiveness and expediency of an application of computer simulation methods for a development of new constructions of reactive cells and the optimization of its geometric parameters are shown. Also, a choice of materials is founded for their production [10]. In the mentioned papers only two regimes, “assembly” (after HPA assembling) and “loading” (after loading of press plant effort to the apparatus for creating the pressure in the working volume) are considered [3, 5-10]. At the same time, certain zones of anvil are subjected to larger stresses under unloading of the apparatus than under its compression. During unloading of press plant effort decapsulation of the apparatus takes place nonsimultaneously in the whole anvil volume. At the beginning pressure falls down to the atmospheric pressure in the circumference part of container situated around the recess. At the same time in inside of the recess high pressure still remains obtained under loading of the apparatus. Therefore in the analysis of HPA workability it is also needed to take into account stresses difference during the transition from one state into another one.

At the “assembly” regime stress-deformed state of anvil arises as a result of its assembly into fastening iron ring of steel rings. At the “loading” and “unloading” regimes anvil is subjected to pressure of press plant supporting plate and reactive cell with container correspondingly under loading and unloading of press plant besides the pressure of side fastening supporter of steel rings.

The aim of this paper is simulation of stress-deformed state of HPA of “anvil with recess” type used by us for the sintering of nanomaterials at the press plant with the effort of 5 MN [11] to optimize its construction and to develop a profitable technology of producing new nanostructured materials based on high melted point solutions with increased physico-mechanical properties.

Appointed apparatus shows itself to good advantage in the experiments of sintering of high melted point ceramics under the pressures up to 4 GPa and the temperatures up to 2200 °C. It distinguishes by increased reactive volume and allows to sinter ceramic specimens with diameters up to 10 mm. It consists of two hard alloy (WC - 6% Co) anvils with diameter of 40 mm and height of 18 mm. At the inverted butt-ends of anvil, the axial recess of trapezium form with diameter of 25 mm at the edge and depth of 8.5 mm are built. The anvils are fastened by three layer iron ring of steel (35HGSA) supporting rings with outer diameter of 150, 110, 76 mm and height of 18, 18, 20 mm accordingly on side surface. The pressure of fastening supporter on anvil is 1.0 GPa.

We consider all three basic regimes of HPA: after assembly, loading and unloading.

2. CALCULATION PROCEDURE

The calculation algorithm is developed to realize the problem assigned, and the program package is made on its base to calculate coordinate and equivalent stresses in the anvil volume using PC [12]. Pressure distribution on working surface of anvil in radial direction under loading of the apparatus is taken in the form of approximation of the curve measured in the paper [13] for anvil with recess with the form of cone connected with a sphere.

The assumption of linear dependence of arising stresses and deformations on loading effort is used for the calculation of stress-deformed state of hard alloy anvils. At this assumption arising deformations in the hard alloy are linearly elastic. In finite element analysis displacements of points in investigated zone are approximated by the discrete model built on the ensemble of piecewise continuous functions defined by concrete values of displacements in finite number of points (knots) of the considered zone.

HPA anvil is uniform and isotropic axial symmetry body with recess form of truncated cone of revolution. At the processes of unloading and loading of pressure effort, loading is carried out along the symmetry axis of HPA. Obviously, that in case of linear dependence of deformations and stresses arisen in anvil on loading effort the distribution of these deformations and stresses in anvil volume has also axial symmetry. Axial symmetry distribution has two degree of freedom. It can be described by two-dimensional distribution, by isolines on the plane of axial section. Therefore in our case the zone split by triangular elements is a half of anvil axial section split by the program on 2403 elements united by 1276 knots.

The components of stress tensor are calculated for every triangular element from obtained displacements of knots [4, 14]. Equivalent stresses are calculated in accordance with the Pisarenko-Lebedev criterion [7], that is the most adequate for the hard alloy [15]:

$$\sigma_{экв} = \chi * \frac{1}{\sqrt{2}} * \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} + \\ + (1 - \chi) * \sigma_1.$$

Here σ_s/σ_c - brittleness coefficient of anvil material, σ_s - creep limit at stretching, σ_c - the creep limit at compressing, σ_1, σ_2, σ_3 - main stresses. The values of σ_s = 0.66 GPa and σ_c = 4,30 GPa for WC - 6% Co hard alloy used in anvil producing are taken from the papers [7, 16-17].

The results of the simulation of stress-deformed state of HPA are presented below. The distributions of radial, tangential and axial stresses in anvil volume as well as distribution of equivalent stresses in volume and on surface of anvil are shown.

3. DISTRIBUTION OF COORDINATE AND EQUIVALENT STRESSES IN ANVIL VOLUME

Distributions of coordinate and equivalent stresses in anvil volume are shown in Figs. 1-3. The largest stress concentration observed at the edge of trapezium recess bottom is a result of these data (the point *A*). The major contribution to the values of equivalent stresses $\sigma_{eq.}$ is the radial σ_R and the tangential σ_θ constituents of stresses tensor at “assembly” regime (Fig. 1). But the values of axial stresses σ_Z = – 0.75 GPa are thrice less in comparison with σ_R = – 2.55 GPa and σ_θ = – 2.12 GPa.

Axial stresses in HPA anvil prevail at “loading” and “unloading” states (Figs. 2-3) with the exception of the zone nearby border of working and side surfaces of anvil, where the radial stresses prevail σ_R = – 0.92 GPa (loading) and σ_R = – 0.93 GPa (unloading).

The radial σ_R and the tangential σ_θ stresses have maximal values nearby the edge of recess bottom at all three regimes (Figs. 1-3). At that, they are compressive at “assembly” regime, and tensile at another regimes. The axial compressive stresses σ_Z mount to maximal values (~4 GPa) close to the yield point at the central part of recess at “loading” and “unloading” regimes (Figs. 2-3). As a result, the equivalent stresses in anvil mount to maximal values at the edge of central recess bottom (the point *A*) at all regimes of HPA. It results from Figs. 1-3. This character belongs to the radial σ_R and the tangential σ_θ components. They have positive values (3.34 and 3.47 GPa) at working regimes: “loading” and “unloading” and negative values (–0.44 GPa) at “assembly” regime.

Arising the radial and the tangential stresses in whole volume of anvil during

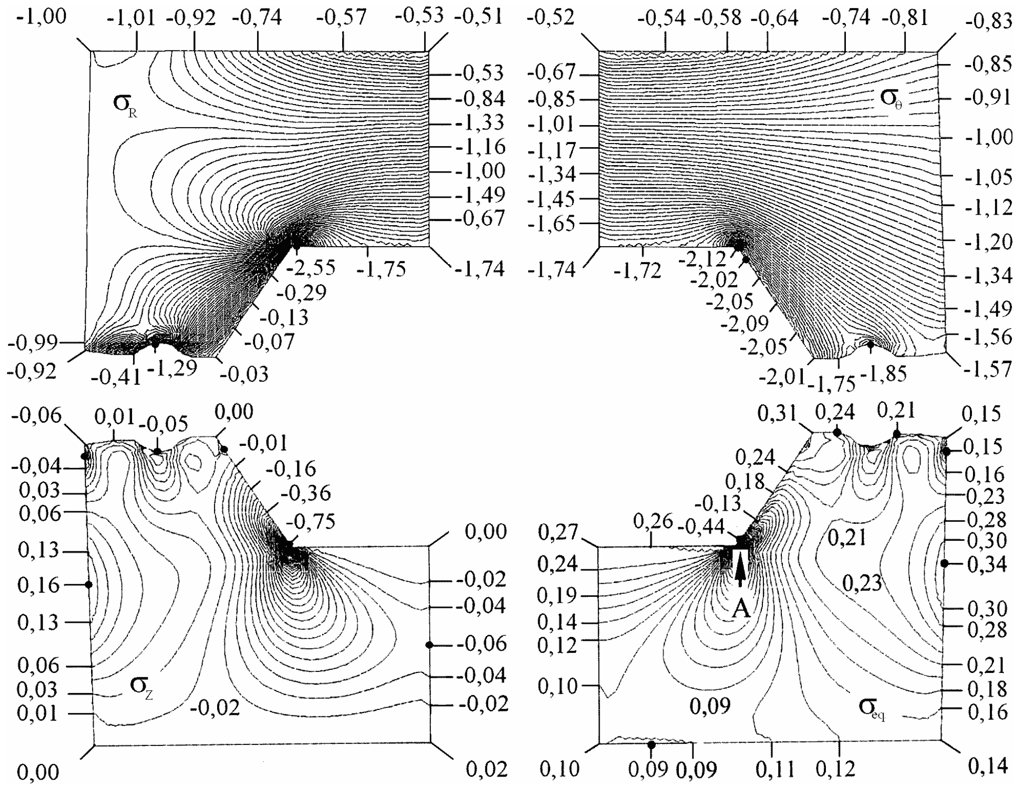

Fig. 1. Distribution of radial σ_R, tangential σ_θ, axial σ_Z and equivalent $\sigma_{eq.}$ stresses in anvil at "assembly" regime, GPa. Interval between stress isolines is 0.023 GPa. *A* - the maximum point of compressive equivalent stresses.

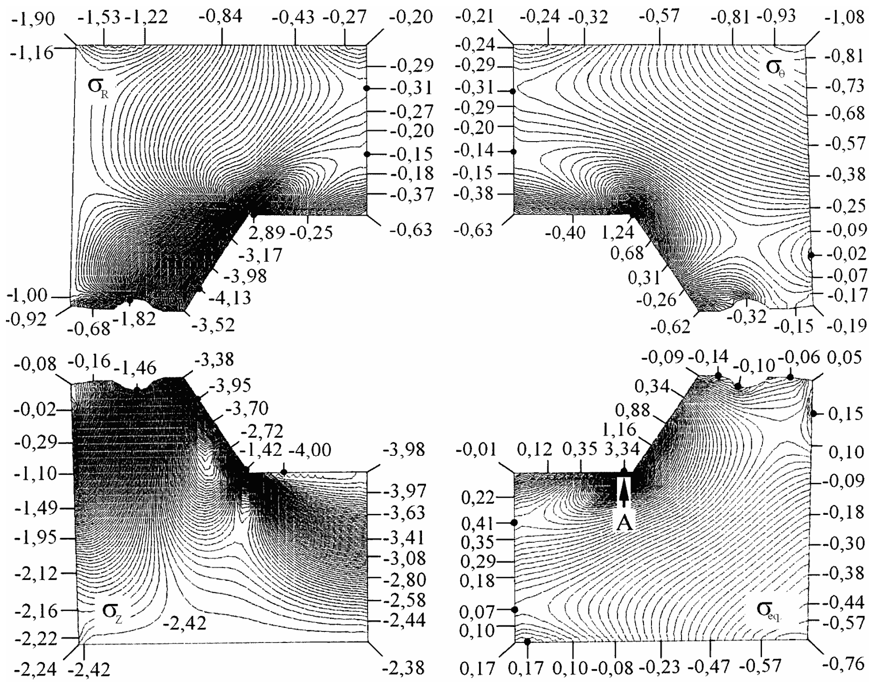

Fig. 2. Distribution of radial σ_R, tangential σ_θ, axial σ_Z and equivalent $\sigma_{eq.}$ stresses in anvil at "loading" regime, GPa. Interval between stress isolines is 0.023 GPa. *A* - the maximum point of tensile equivalent stresses.

assembly of the HPA are compressive. At that, their values are much lower than the yield point (4.30 GPa) (Fig. 1). The peripheral part of anvil in side surface is under insignificant axial tensile stresses, the inside part is under compressive stresses (Fig. 1).

Sizeable part of anvil volume is characterized by the radial and the tangential compressive components of stresses excepting for the zone nearby the edge of recess bottom during a working of the apparatus ("loading" and "unloading" regimes) (Figs. 2 and 3). Small tangential tensile stresses arise at the central part of anvil base surface under unloading of the apparatus (Fig. 3).

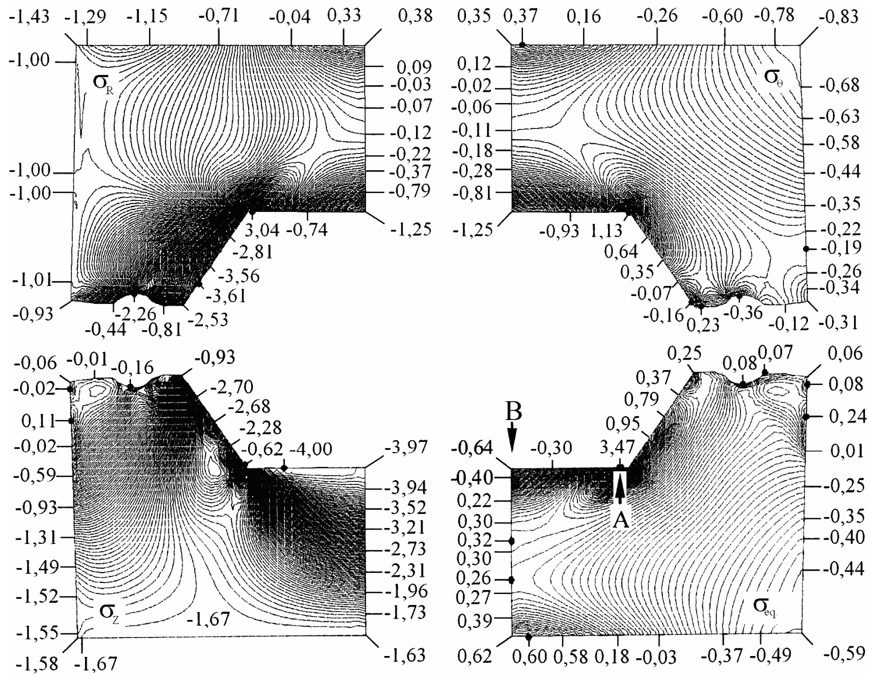

Fig. 3. Distribution of radial σ_R, tangential σ_θ, axial σ_Z and equivalent $\sigma_{eq.}$ stresses in anvil at "unloading" regime, GPa. Interval between stress isolines is 0.023 GPa.
A - the maximum point of tensile equivalent stresses.
B - the maximum point of compressive equivalent stresses.

4. DISTRIBUTION OF EQUIVALENT STRESSES ON ANVIL SURFACE

The distributions of equivalent stresses along the symmetry axis and also at the base, the side and the working surfaces of anvil are shown in Fig. 4. Certain zones being concentrations of stresses on anvil surface are determined from this figure. At the same time the character and the level of stresses in anvil at "assembly" regime considerably distinguish from "working" regimes of HPA anvil, "loading" and "unloading".

In general evenly distributed positive stresses are typical for whole anvil surface at "assembly" regime. Stresses are negative only at the ring zone nearby the edge of recess bottom at "assembly" regime, but positive at "loading" and "unloading" regimes (Fig. 4d). An abrupt changing of stress value is observed under "loading" and "unloading" of HPA in this place from -0.44 GPa to 3.34 and 3.47 GPa correspondingly.

Changing character of the equivalent stresses along the anvil axis at "assembly" regime (Fig. 4a) testifies distribution evenness of positive stresses, but at working states, "loading" and "unloading", the distribution curves have a positive maximum nearby the recess bottom, -0.41 and 0.32 GPa correspondingly.

Evener distribution of the equivalent stresses is observed on the base surface of anvil at “assembly” regime (Fig. 4b). However a changing range of equivalent stresses is extremely large under “loading” and “unloading” of the apparatus, especially under “unloading” state, from -0.76 to 0.17 GPa (loading) and from -0.59 to 0.62 GPa (unloading).

The distribution of the equivalent stresses along side conical surface of anvil is uneven at “assembly” regime (Fig. 4c). At “loading” and “unloading” regimes of HPA in direction from base to working surfaces of anvil the level of negative stresses decreases achieving a zero value nearby the top edge of anvil side surface. Positive stresses are characteristic of the top of anvil side surface under “loading” and “unloading” of HPA.

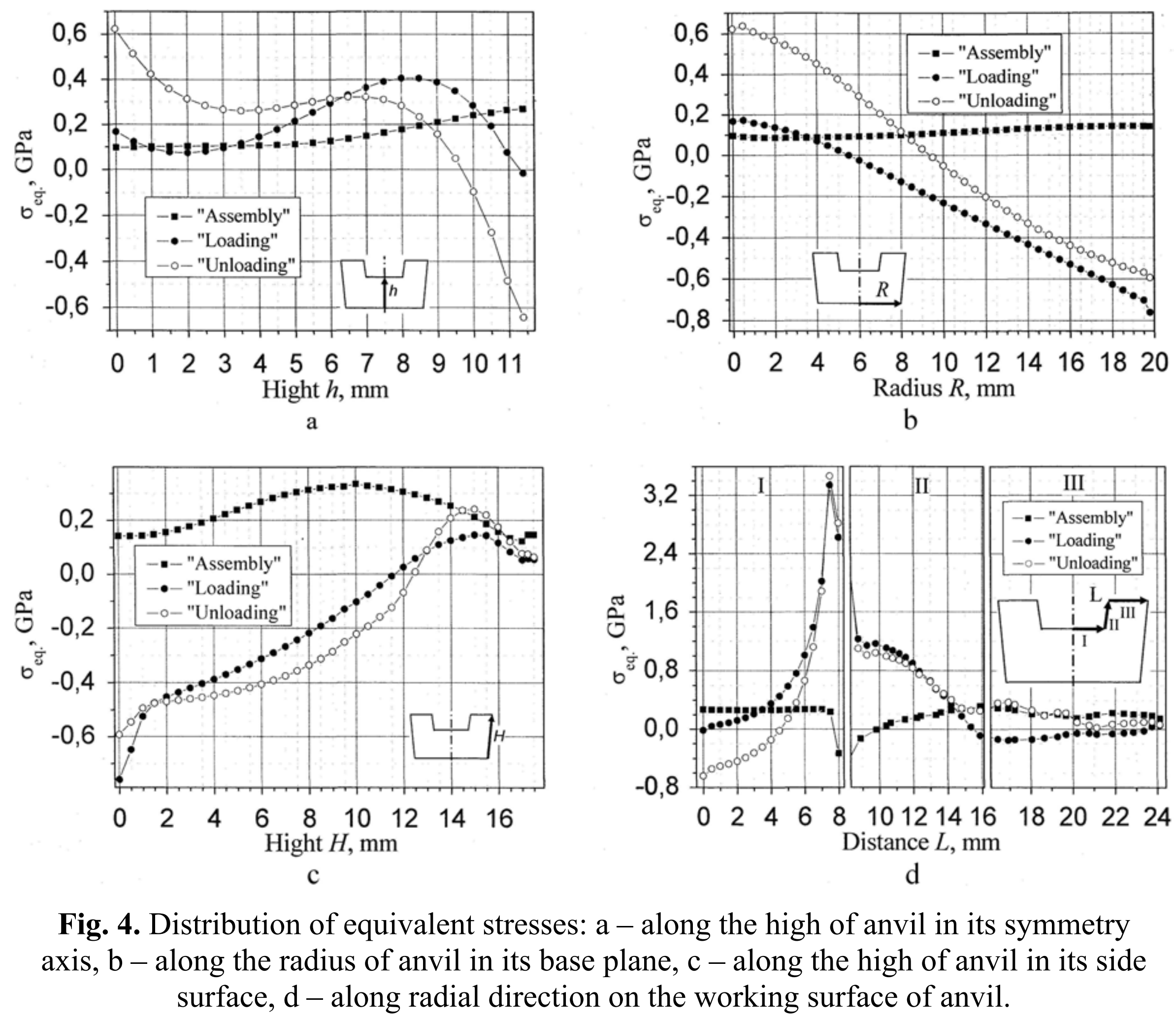

Fig. 4. Distribution of equivalent stresses: a – along the high of anvil in its symmetry axis, b – along the radius of anvil in its base plane, c – along the high of anvil in its side surface, d – along radial direction on the working surface of anvil.

Results of calculation demonstrate that the basic feature of distribution of equivalent stresses on the working surface of anvil in radial direction (Fig. 4d.) is an interchange of alternating equivalent stresses at HPA working at various states. Especially the circular zone nearby the edge of recess plane bottom at the zone I has a big drop of stresses. This testifies to the greatest probability of destruction in this place. Whereas maximal changes occur because of the radial stresses σ_R (Fig. 2-3), in general a distraction is characterized in the form of circular cracks. Tangential stresses also make a great contribution into anvil destruction.

Note also, that the maximal drop of axial stresses (Figs. 1-3), from 0 to -3.98 GPa under loading and from -3.97 to 0 GPa under unloading occurs in the central zone of recess bottom (the zone I in Fig. 4d). Distribution of equivalent stresses in the zone II and III (Fig. 4d) of working surface of anvil are more uneven than in the zone I.

5. ANVIL ZONES WITH DESTRUCTIVE STRESSES AND CHARACTER OF THEIR DESTRUCTION

Analysis of stress-deformed state of anvil (Figs. 1-4) reveals that the distribution of distractive stresses in anvil volume and on anvil surface is uneven. There are zones with extremely high level of equivalent stresses on anvil surface. In Figs. 1-3 these zones are marked by the points *A*, *B*. At first just these zones subjected to the largest cyclic loadings will be destroyed

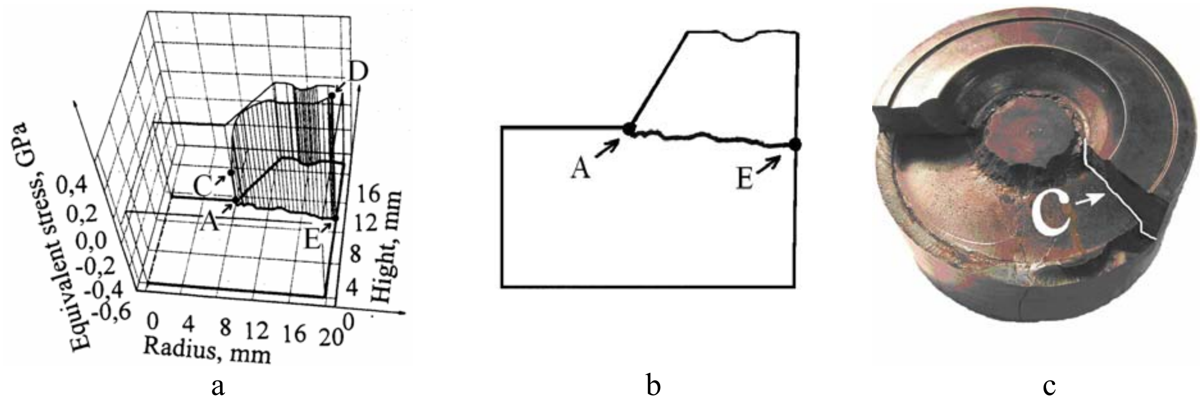

Fig. 5. Line of extremal differences of equivalent stresses in the anvil at transition of HPA from “unloading” to “loading” regimes (a, b) and characteristic picture of destruction surface of anvils (c) in the issue of HPA multiloading.

during an exploitation process of HPA. Therefore it is very important to provide at the indicated points in the construction of HPA during a working process as far as possible the lowest level of stresses. This guarantees longer service time of anvil. The most critical point at anvil surface is the point *A* at “loading” and “unloading” regimes (Figs. 1-3). It is a result of Fig. 4d. Because in this place equivalent tensile stresses rich maximal values.

Apparently, high cyclic sign-changing stresses in anvil are the reason of ring turning-up of and radial crackings. It is able to determine extremal stresses and the profile of anvil destructive surfaces having built the distribution surfaces of equivalent stresses on the whole square of axial section at different regimes. On the base of the calculation of sign-changing cyclic stresses distribution surface in the axial section of anvil, where every its point is the value of equivalent stresses difference between the regimes “unloading” and “loading”, the position of line *CD* of such surface extremal values (Fig. 5a) and its projection, line *AE*, onto the plane of anvil axial section shown at the Fig. 5 a and b are determined. The line *AE* in the plane of anvil axial section determines the profile of its destruction basical surface. The results of our calculations of HPA anvils destruction surface are sufficiently close to the real picture of destruction (Fig. 5c). The line *AE* corresponding to the points with extremal values of sign-changing cyclic equivalent stresses at Fig. 5 a, b approximately coinsides with the line *c* at Fig. 5c. The destruction of real anvil takes place along this line.

Thus obtained results testify, that the real picture of anvil destruction in a working process of HPA and the character of stresses distribution calculated by us are in accordance with each other. It testifies about adequacy of developed calculation methodic.

6. CONCLUSIONS

Calculation of stress-deformed states of high pressure apparatus (HPA) of "anvils with recesses" type for sintering of nanomaterials is realized by finite element analysis (FEA). At first three general regimes of HPA: "assembly", "loading" and "unloading" are considered together. It is shown, that in certain zones of HPA hard alloy anvils arisen stresses as a result of pressure difference in the interior and from the outside of the apparatus are higher at the apparatus unloading than at the apparatus loading. At loading and unloading of HPA tensile stresses riches the maximal values at the edge of trapezoidal recess bottom of anvil. At this place the destruction probability is high. At the "assembly" regime these places are underwent under compressive stresses affect. It is obtained, that the real picture of anvil destruction during a working process of the HPA and the character of stress distribution in anvil volume calculated by us are sufficiently good conformed with each other.

The invented methodic and obtained results will be used for the modernization of described apparatus construction and solution of similar problems at development of others constructions of HPA of "anvils with recesses" type.

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