METHOD OF PERMEABLE ELEMENTS FOR SIMULATION OF POWDER METALS FORMING PROCESSES

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Abstract. For simulation of processes of compaction or forging of products from powder materials, a method of permeable elements is proposed. The essence of the method is to use elements whose shape is regulated in advance, and, unlike the finite element method, where the elements coincide with the material volumes and their masses are unchanged, here the masses elements are variable, and material can flow between adjacent cells. Examples of using the method for modeling the processes of forging of porous preforms in closed and open dies, as well as in a closed die with a compensation cavity, are presented.

Keywords: powder materials, simulation, numerical methods, forging, porous body, plasticity criterion.

1. Introduction

Among the numerical methods for solving problems associated with finding the stress and strain fields that arise both in compact and in porous materials, the finite element method (FEM) has become widespread. Its advantages include convenience in terms of algorithmization and programming, as well as the relatively high accuracy of the resulting solutions [1-4].

However, in the study of technological processes during which large deformations develop, the use of FEM is sometimes difficult due to excessive distortions of the finite element mesh. In particular, with large axial deformations, local flattening of the cells is possible, which is especially important for bulk compressible materials, since it may not be possible to calculate the density distribution. From a purely technical point of view, this regularization necessitates the regeneration of the grid every few counting steps, significantly increases the counting time, and significantly complicates the solution algorithm.

To solve the technological problems of this type, it seems more appropriate developed in Institute for problems of materials scence NAS of Ukraine so called method of permeable elements (MPE). Its essence consists in the use of elements whose shape is regulated in advance, and, unlike the FEM, where the elements coincide with the material volumes and their masses are unchanged, here the masses of the elements are variable - material can flow between adjacent cells.

2. Objects and research methods

When constructing an algorithm for modeling the processes of compaction and deformation of porous preforms during their processing by pressure using the method of permeable elements, we used the model of an ideal rigid plastic porous body. The physical and mathematical formulation of the problem is based on the following basic assumptions.

A porous preform is an isotropic compressible body to which the basic equations of continuum mechanics are applicable. In the framework of this approach, a porous body is considered as a chaotic mixture of solid and emptiness. In accordance with the basic concepts of continuum mechanics, it is also assumed that the behavior of the elements under consideration can be described using the strain rate tensor e_{ij}, stress tensor σ_{ij}, relative density ρ or porosity θ and a number of other parameters [5].

The proposed method is designed to solve problems in a quasistatic formulation and its implementation can conditionally be divided into the following three stages:

- specifying a sampling structure and determining the corresponding form functions for the velocity field;
- determination of the velocity fields all over the processed material;
- determination of the field of densities, deformations, stresses and other deformation parameters.

The first of these stages is characterized by the fact that, unlike the FEM, the movement of the mesh in the MPE (if this is realized) is not associated with the movement of particles of the pressed material, but is independent of it and is determined based on the convenience of analyzing the results. The latter is due to the use of the motion of the deformable material as the basic Eulerian idea. In this regard, the mass of each element can be variable, and the elements themselves are permeable.

The grid of permeable elements and the evolution of their shape during processing are set a priori based on known data on the nature of the movement of the processing tool, the convenience of the analytical representation of the functions of the velocity fields, and also on the basis of the possibility of further experimental verification. The foregoing also constitutes one of the advantages of the MPE, since it simplifies the procedure for comparing the results obtained by experimental and computational methods; there is no need to use averaging operations that reduce the accuracy of the obtained solution.

At the same stage, by analogy with the FEM, kinematic parameters are determined as a function of shape through their unknown values at the grid nodes. In the general case, the MPE grid can be constructed as in the FEM, however, the movement of the nodes is no longer controlled by the velocity field of the material flow.

As a basic model for describing the processes of hot deformation of porous materials, the model of a plastic porous body [5] is used based on the assumption that there is some plasticity criterion F, which relates the components of the stress tensor with porosity:

$$F = \frac{p^2}{f_1(\theta)} + \frac{T^2}{f_2(\theta)} - \sigma_s{}^2 = 0 \qquad (1)$$

where $f_1(\theta)$ and $f_2(\theta)$ are some functions of the material porosity θ, which determine its rheological properties; σ_s is the yield strength of the base material for these temperature-strain conditions.

The basic algorithm for solving problems using the method of permeable elements, based on the application of variational methods, includes the following operations. For the investigated volume of the deformable billet, some functions of the velocity field corresponding to the boundary conditions are set in the form of polynomials:

$$v_k = a_1\varphi_1(k) + a_2\varphi_2(k) + \cdots + a_n\varphi_n(k) \qquad (2)$$

where k is the generalized coordinate; $\varphi_i(k)$are some coordinate functions; a_i - numerical coefficients - unknown variable parameters, the value of which at each step of deformation is selected using one of the known optimization methods in such a way that it minimizes the value of the functional J:

$$J = \sum_{k=1}^{K}\iiint_V \sqrt{e^2 \cdot f_1(\Theta) + H^2 \cdot f_2(\Theta)} \cdot dV + \sum_{m=1}^{M}\sqrt{3}\iint_F \mu\sqrt{f_2(\Theta)\cdot(v_1^2+v_2^2)}\cdot dF; \qquad (3)$$

where $e = e_{ij}\delta_{ij}$ is the first invariant of the strain rate tensor characterizing the speed of uniform comprehensive compression (or tension), which can be defined as

$$e = \frac{1}{\Theta}\frac{d\Theta}{dt} = \frac{1}{V}\frac{dV}{dt};$$

H_i - shear strain rate intensity; dV is the elementary volume of the deformable body; μ is the coefficient of friction; v_1 and v_2 are the components of the velocities of the particles of the deformable body along the contact surfaces (at the workpiece – tool interface); dF is the elementary area of the contact surface.

Having determined the values of the varied parameters a_i, we can find the velocity field functions (2) and calculate the components of the strain rate intensity Hi and the compaction rate e, which allows us to solve the problems of final shape change and determine the force and energy parameters of the process.

The density distribution field is found from the law of conservation of mass, which for any element of a continuous medium is formulated as:

$$\frac{dm}{dt} = \int_S v_n \rho \cdot dS \qquad (4)$$

where m is the mass; t is the time; v_n is the projection of the flow velocity vector of the material of a given permeable element onto the normal to the surface S bounding this element.

When assuming the existence of velocity discontinuities in a deformable body, it is also necessary to take into account the energy expenditure on deformation on the discontinuity surfaces in the main energy equation. In view of the foregoing, functional (4) takes the form [6]:

$$J = \sum_{k=1}^{K}\iiint_V \sigma_{ij} \cdot e_{ij} \cdot dV + \sum_{m=1}^{M}\sqrt{3}\iint_F \mu\sigma_s\sqrt{f_2(\Theta)\cdot(v_1^2+v_2^2)}\cdot dF + D; \qquad (5)$$

where D is the power dissipation on the discontinuity surfaces of kinematically possible displacement velocities. The rupture surface is considered as the limiting position of a thin transition layer of thickness Δn at $\Delta n \to 0$, in which the displacement velocity undergoes a fast but continuous change.

The magnitude of power dissipation on the surface of the velocity gap can be determined as [6]:

$$D = \int_\Sigma \sigma_s \sqrt{(\Delta v_n)^2 f_1(\Theta) + \left[\frac{4}{3}(\Delta v_n)^2 + (\Delta v_t)^2\right] f_2(\Theta)} \cdot d\Sigma \qquad (6)$$

where $d\Sigma$ is the elementary surface of the velocity gap; Δv_n and Δv_t are the normal and tangent components of the discontinuity velocity vector.

If to take the values of the functions $f_1(\theta)$ and $f_2(\theta)$ in the form of dependencies:

$$f_1(\Theta) = \frac{4}{9}\cdot\frac{(1-\Theta)^4}{\Theta}; \qquad f_2(\Theta) = \frac{(1-\Theta)^3}{3}; \qquad (7)$$

then we can write:

$$D = \int_\Sigma \frac{(1-\Theta)^{3/2}}{\sqrt{3}}\sigma_s\sqrt{\frac{4}{3\Theta}(\Delta v_n)^2 + (\Delta v_t)^2} \cdot d\Sigma; \qquad (8)$$

3. Results and their discussion

The developed general MPE algorithm was successfully used, in particular, to simulate the processes of closed and open hot forging and forging of porous preforms in a half-open die, compaction of bimetallic porous preforms with a horizontal separation plane, precipitation of an annular porous preform in a closed die with a free centripetal radial flow of material, consolidation of step products such as a sleeve with a shoulder, etc.

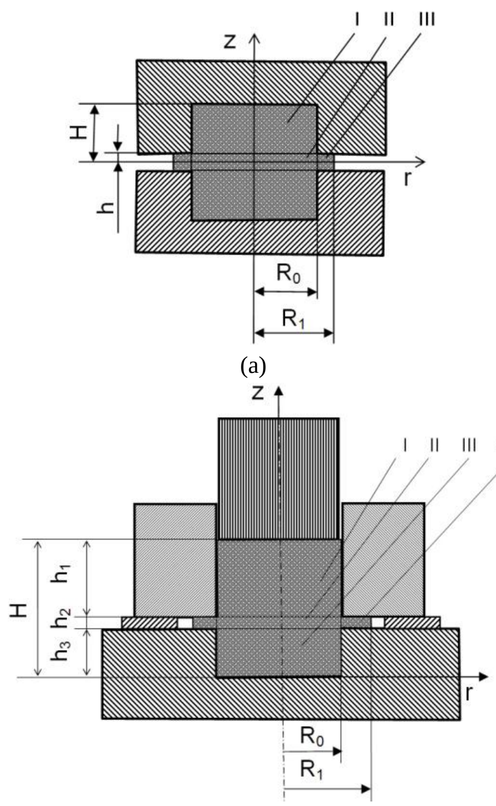
In particular, we give examples of the use of the considered method for studying the mechanics of material flow during open hot forging of porous preforms (Fig. 1, a) and closed forging in a die with a compensation cavity (Fig. 1, b).

The effectiveness of the application of hot forging methods for powder products in dies with open volumes at which additional shear deformations are realized along with axial ones is shown in a number of works [7-9].

At the same time, hot forging of porous preforms in an open die, a distinctive feature of which is the presence of a height-changing section of the preform with a free lateral surface throughout the deformation process, was not widely used, since uncontrolled extrusion of the material being compacted is possible in the flake in the early stages of deformation, which may cause under-compaction of the forging material.

In this regard, questions of studying the mechanics of the flow of the workpiece material during forging in dies having additional compensation cavities are of practical interest.

The calculation model for describing the flow of a porous material during hot open forging and closed forging in dies with a compensation slit was constructed on the basis of the variational principle, while material hardening, temperature effects and inertia were neglected, and the method of permeable elements was used as a numerical method for implementing the model.



(b)

Fig. 1. *The design models for the processes of open forging (a) and closed forging in a die with a compensation gap (b)*

Taking into account the symmetry of the deformable workpiece relative to the vertical axis, the calculation was made for half of its cross section, which was conditionally divided into three design zones (permeable elements) for open forging (Fig. 1, a), and four zones for closed forging (Fig. 1, b). Inside each of the calculated elements, the distribution of density and strain rates at different compaction times is considered homogeneous.

The boundary conditions for the velocity components v_z and v_r can be expressed as:

$v_z|_{z=H} = -v_0$; $v_r|_{z=H} = 0$; $v_z|_{z=0} = 0$; $v_r|_{r=0} = 0$; $v_z|_{z=h} = -v_0$;

where v_0 is the velocity of the upper half-matrix.

Assuming that the velocities in each of the forgings calculated zones are linear functions of the r and z coordinates, taking into account the boundary conditions, we take the following expressions describing the velocity field of the material flow in each of the zones:

open forging:

zone I: $v_z = -v_0 \dfrac{z}{H}; \quad v_r = 0;$

zone II: $v_z = -v_0 \dfrac{z}{H}; \; v_r = \dfrac{v_0}{h} a_1 r \nu;$ (9)

zone III:

$$v_z = -v_0 \frac{z}{h}; \; v_r = \frac{v_0}{h} a_1 R_0 \nu \left(1 + a_2 \frac{r - R_0}{R_1}\right);$$

closed forging:

zone I: $v_z = v_{12} - \dfrac{v_0}{H}(z - h_2 - h_3); \quad v_r = 0;$

zone II: $v_z = v_{23} - \dfrac{v_0}{H}(z - h_3); \quad v_r = \dfrac{v_0 r}{H a_1 \nu};$

zone III: $v_z = -\dfrac{v_0 z}{H}; \quad v_r = 0;$ (10)

zone IV: $v_z = 0; \quad v_r = \dfrac{v_0 R_0}{H a_1 \nu}\left\lfloor 1 + a_2 \dfrac{(r - R_0)}{R_1} \right\rfloor;$

where a_1 and a_2 are some variable parameters; v_{12} and v_{23} are the linear flow rates of material between zones I-II and II-III respectively (closed forging).

After the corresponding transformations, taking into account dependences (9) and (10), the form of the components of the functional J was determined and, taking the parameters σ_s, μ and v_0 as constant throughout the deformation cycle, at each calculation step we found the values of a_1 and a_2 that minimize the functional (5).

The calculation was carried out using the step loading method, in accordance with which the entire deformation period was divided into equal time intervals Δt, during which the workpiece is upseting at $\Delta H = = v_0 \cdot \Delta t$. At each i-th loading step, the parameters a_1 and a_2 were determined that minimize the functional J; from (9) and (10) a new value of the flash radius R_1 was found from the dependence:

$$\Theta_k^{н} = 1 - \frac{m_k \pm \dfrac{dm_k}{dt}\Delta t}{V_{н}^{k}\gamma} \qquad (11)$$

where $\theta^{н}_k$, $V^{н}_k$, and m_k are the porosity, volume and mass of the k-th zone of the preform, respectively, after the next step of deformation, the current values of porosity in individual zones of the preform were calculated.

Comparison of the simulation results of the hot forging process in an open die with similar data for forging in a closed die with compensators showed that while during forging in an open die the displacement of material in the flash starts already at the initial stages of deformation (Fig. 2), then in a closed die with compensators - only after the workpiece reaches a certain threshold, sufficiently high density level (at $\theta = 2 \div 5$ %) (Fig. 3), which leads to a decrease in the final value of the flash size during forging in a die with a compensator.

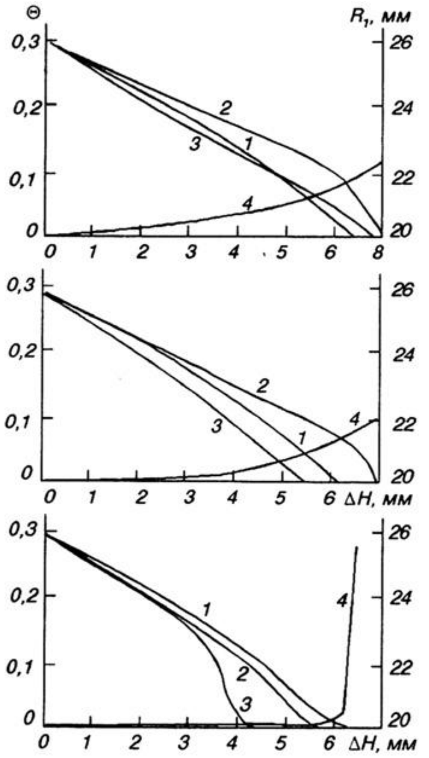


Fig. 2. *The dependence of the current porosity of the material in the zones: I (1), II (2) and III (3) and the radius of the flash (4) from axial deformation at h_0 = 11 (a), 9 (b) and 7 (c) mm; θ_0 = 0.3*

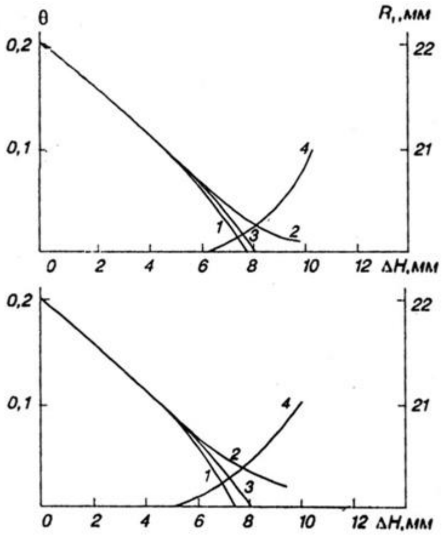


Fig. 3. *The dependence of the current porosity of the material in the calculation zones I (1), II (2), III (3) and the radius of flash (4) at the axial strain ΔH for h_2 = 3.0 (a) and 4.0 (b) mm; θ_0 = 0.2*

At the same time, a sharp increase in the resistance to metal outflow in the flash at the final stage of open forging due to the gradual closure of the half-matrices, contributes to the compaction of the material in the second zone, while at closed forging with a compensator, due to the constant gap between the half-matrices, the resistance to outflow to the store changes slightly, which determines the presence of some residual porosity in zone II of the forging.

It should be noted also that, in contrast to open forging, in which the choice of optimal porosity, the ratio of the size of the workpiece and the cavity of the matrix has a significant effect on the density distribution in different parts of the forging and the final value of the flash, then when implementing a closed forging scheme with compensators, the dependence of the qualitative characteristics forgings from the specified structural and technological parameters are significantly lower. This fact, along with the fact that the flash value is reduced during forging in a closed die with a compensator, ceteris paribus, allows us to conclude that the scheme under consideration is preferable to open forging. At the same time, it should be noted that the structural complexity of die tooling for the implementation of the closed forging process with compensators somewhat limits the possibility of its wider use in industry.

Information on the power parameters of the processes under consideration is essential when choosing a deformation scheme and brand of a press, as well as in calculating die tooling. Let us consider, along with the above schemes, the traditional closed powder forging scheme without compensation slots, traditional for powder metallurgy.

The forging forces for the three considered deformation schemes were calculated using the basic equation of the energy method.

Analysis of the simulation results, which are presented in Fig. 4 shows that the use of a closed forging scheme necessitates the application of significantly higher forces to obtain high-density forgings. The smallest deformation force is with open forging. These results allow us to conclude that with an increase in the rigidity of the loading circuit, the strain force increases. It is noteworthy that the difference in effort increases with increasing degree of axial deformation, and hence the average density of forgings. At the initial stages of compaction, the difference in the efforts for the considered deformation schemes is small.

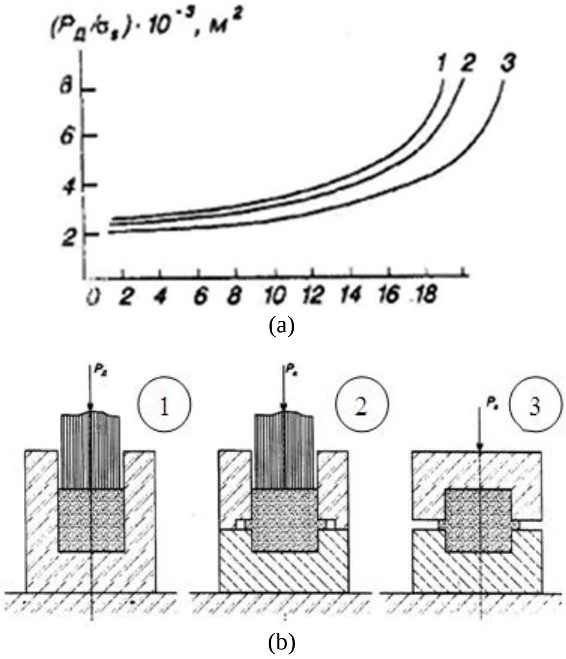


Fig. 4. *The dependence of the relative value of the forging force on axial deformation (a) for deformation schemes (b): 1 - closed forging; 2 - forging in a closed die with a compensator; 3 - open forging*

It should be noted that experimental studies of the processes of hot forging of powder samples lead to similar results [8-10]. The use of compensation slots allows to obtain high-density forgings with a homogeneous structure at a lower strain pressure compared to traditional closed forging.

Thus, the presented results allow us to conclude that the traditional scheme of hot forging of porous preforms in a closed die is the least preferred in terms of energy and process parameters. This indicates the advisability of using less rigid deformation schemes with partial extrusion of the workpiece material into the compensation cavities.

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