Models for calculating residual porosity and stresses in powdered iron produced in a rigid matrix

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The features of deformation of a powder medium consisting of plastic (iron) and elastic (cast iron) particles are considered. To solve the problem of deformation of such a system, the model of continuum mechanics is taken as a basis, although after compaction of the powder mixture it consists of a matrix and pores, which is called a powder or porous medium. In this case, to apply the continuum principle, the space region is divided into small subregions corresponding to the sizes of powder particles. It is assumed that the material is isotropic and for this case the invariants of the stress tensor and deviator are written. In this case, the loading surface is convex, closed, or has a rib-type feature, or can be smooth. In the latter case, deformation of the iron-cast iron powder system occurs on the edge of a piecewise smooth surface. At the same time, the work considers the schemes of an axisymmetric problem in cylindrical coordinates and obtains a group of equilibrium and continuity equations in the Euler representation. The relationships of the associated strain rate law are related to stresses, and they are solved for a smooth surface and a piecewise smooth surface. The models were obtained for the case of a pressing scheme in which there is mutual movement of the matrix and the internal rod of the matrix. Based on this, the displacement of the upper punch and die was determined. For such movement of mold elements, specific properties of the kinematic field were obtained. The contribution of tangential friction of iron and cast iron powders on the matrix wall has been clarified. This mathematical problem allows you to control the technological processes of cold pressing of an elastically plastic medium of a mixture of iron and cast iron powders. At the same time, for a blank such as a sleeve, the requirement to ensure the required porosity and dimensions is solved, and it also becomes possible to determine the required pressing force, punch stroke and distribution of residual porosity

Key words: elastic-plastic medium, continuum mechanics, iron, cast iron, discrete nature, mathematical model
DOI: 10.17580/cisisr.2026.01.16

Introduction

Due to the discrete nature of powder matrices and porous bodies, and primarily their ability to reversibly change their volume, a continuous description of these issues has a number of peculiarities. However, the powder medium or framework of a porous body contains both powder particles and pores, which raises the following question: the concept of powder medium continuity should be understood as the combination of the powder body and the pores.

If we apply the well-known concepts of multiphase systems [1, 2] to these materials, the answer to this question can be formulated as follows: a particle of the medium should be understood as a region of space, the dimensions of which are smaller than the sample as a whole and at the same time significantly exceed the dimensions of individual powder particles, pores, or the distance between them. The combination of such regions is called a powder or porous medium. When applying the continuum principle, the region of space in which the medium under study is located is divided into small subregions, the size of which coincides with the dimensions of the particles of the medium. The subregions themselves are identified with points in the space filled with the medium. In this case, the state of this medium is determined by the kinematic, dynamic, and thermal parameters of the process of its compaction [3]. Therefore, the study of the compaction process of a powder composite of the iron-cast iron type in relation to the above-mentioned parameters is of particular interest.

Literature review and problem statement

Cold pressing methods with mutual displacement of pressing elements have found wide application in powder metallurgy for the production of composite blanks of relatively complex configurations [4]. The pressing scheme is determined by the established type of laws of motion of the pressing elements. However, the work [4] does not consider cold pressing of an elastic-plastic medium such as „iron cast iron“. At the same time, the influence of the pressing scheme and the medium on the distribution of the main characteristics of the formed product within its volume has not been sufficiently studied theoretically. The work [5] also does not take into account the study of stresses and densities by existing methods, as well as the pressing scheme and medium during cold forming.

In [6], the behavior of a compacted metal powder or powder mixture is described within the framework of continuum mechanics. The following well-known assumptions are made:

– the material is quasi-isotropic at all times;

– effects leading to asymmetry of the stress tensor are absent during deformation;

– the rheological properties of the material can be described locally by the relationships between the characteristics and the state of the medium;

– inertial effects can be neglected in all subsequent considerations.

However, this work, as is implied by the assumptions adopted, does not take into account the relative movement of the mold elements, i.e., the inertial effects of the process of forming an elastic-plastic mixture.

The first three assumptions [7] are based on experience in soil and bulk solids mechanics. When the load application rate is low, the last assumption is typical of the static cold pressing of a powder medium. The experimental justification for this assumption forms the basis of the continuum model used. This assumption indicates that the material pressed under the given conditions is plastically hardening.

However, this paper considers only a plastic medium, that is, the state in which the iron powder is deformed, and does not mention the combined deformation of iron and cast iron powders. However, it should be noted that when deformation occurs in an elastic-plastic medium, the strengthening process of the formed workpiece can change significantly, and therefore, so can the invariants of the stress tensor and deviator for assessing the system‘s deformed state. Both the addition of a hard particle (cast iron powder) to the charge, the strengthening of the iron powder in its environment, and changes in porosity cause strengthening of the powder composite as a whole. Therefore, these processes cannot be considered in isolation.

In [8], the results of strain hardening of iron-cast iron metal powders are presented; however, the author does not take into account the rheological properties of the deformed powder body. Consequently, three types of hardening under monotonic loading are clearly interconnected: the plastic flow of the iron powder, the rigid resistance of the cast iron powder to the movement of the plastic medium, and the rheology of the system as a whole. This can be considered a fairly reasonable assumption, since the initial parameters of the cast iron powder and the porosity value at the current moment of deformation can be taken as hardening parameters.

Research Objectives and Tasks

The objective of this study is to develop mathematical models for calculating residual porosity and stresses in the bulk of an axisymmetric component made of an iron-cast iron powder composite.

To achieve this goal, the following tasks were set:

– construct a diagram of the arrangement of various particles and pores of the elastoplastic composite before molding;

– determine the conditions for constructing mathematical models for strengthening the iron-cast iron composite under different loading surfaces;

– solve a mathematical problem for a smooth loading surface;

– solve a mathematical problem for a piecewise smooth loading surface.

Raw Materials and Method for Cold Pressing an Iron-Cast Iron Powder Mixture

The following raw materials were used: ASC 100-29 iron powder (produced by the Swedish company Noeganaes) obtained by atomization, and a powder of special gray cast iron with interdendritic point graphite obtained by ball milling chips of the corresponding cast iron formed during the machining of castings. It should be noted that the ASC 100-29 iron powder was obtained by water atomization, therefore it has a somewhat poorly developed surface with almost no intraparticle pores. The average particle size of the iron powder was 100 mesh, and that of the cast iron was 120 mesh. A process lubricant, zinc stearate, was added to the powder mixture in an amount of 0.8 % of the total mixture weight. The ratio of iron and cast iron powders in the mixture was 1:1. The powders were mixed in a Japanese 3D mixer for 30 minutes, followed by cold pressing using a Bussman Simetag HPM 100S hydraulic press (Germany) at 400–1000 MPa using a floating die. While filling the die, a suction mode was used to maximize air drainage from the powder mixture.

Development of Models for Strengthening the Iron-Cast Iron Composite

Schematic diagram of the arrangement of iron and cast iron powder particles in the die before pressing

Fig. 1 presents an approximate physical model for the arrangement of iron and cast iron powder particles, as well as the pores formed between them as a result of filling the mixture into the die in the „suction“ mode. In this case, the location of the process lubricant, zinc stearate, is not shown in the model, as it is applied to the surfaces of the metal particles.

Fig. 1 shows that the cast iron powder particles are finer than those of iron powder, have a relatively smooth surface, and therefore quickly occupy empty spaces when the matrix is filled in the „suction“ mode. As can be seen from the figure, the pores are located predominantly in the space between the non-contacting surfaces of the elastic and plastic particles. It is reasonable to assume that the arrangement of the two dissimilar particles will be chaotic, and therefore, during pressing, either a smooth loading surface (iron–

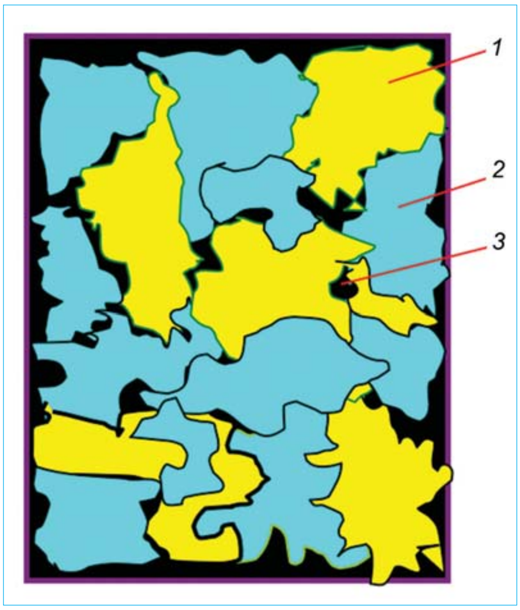

Fig. 1. Diagram of the arrangement of the mixture of powder particles of iron and cast iron in the matrix before pressing: *1* – iron – matrix; *2* – cast iron filler; *3* – pore

iron particles) or a piecewise smooth loading surface (iron-iron particles) can occur. Therefore, the strengthening of such a composite during cold deformation in a rigid matrix can be complex.

Determining the conditions for constructing a mathematical model of composite hardening

Based on the general laws of mechanics of a composite hardened by plastic deformation, it follows that in this case there is a relationship between the porosity and the components of the stress tensor, which can be called the hardening condition [9, 10]. Based on the assumption of quasi-isotropy of the material, this condition contains the tensor invariants and the stress deviator, and it has the form:

$$f\left(q_1, q_2, \theta\right) = 0\,, \tag{1}$$

where

$$q_1 = \sigma_{ij}\delta_{ij}\,, \tag{2}$$

$$q_2^2 = \left(\sigma_{ij} - \frac{1}{3}q_1\delta_{ij}\right)\left(\sigma_{ij} - \frac{1}{3}q_1\delta_{ij}\right), \tag{3}$$

σ_{ij} – stress tensor, δ_{ij} – strain tensor, θ – porosity.

Methods for describing changes in the mechanical properties of metallic powders and mixtures show that the function f corresponds to a loading surface in the stress tensor‘s representation space. This surface is convex, closed, and either has a singularity or edges, and can be smooth. In the latter case, deformation is analytically expressed by satisfying the following two conditions and occurs on the edge of a piecewise smooth surface.

$$(q_1, q_2, \theta) = 0, \tag{4}$$

$$\psi(q_1, q_2, \theta) = 0, \tag{5}$$

where ψ and q are smooth functions of their arguments.

We have considered schemes for forming an axisymmetric problem in cylindrical coordinates. At the current moment of deformation, the stress-strain state is considered, therefore, it is appropriate to use the Euler representation.

The relationships of the associated strain rate law are related to stresses, which for a smooth loading surface have the following form:

$$e_{ij} = \mu\frac{df}{d\sigma_{ij}}, \tag{6}$$

(e_{ij} is the strain rate tensor), and for piecewise smooth it is taken in the form:

$$e_{ij} = \upsilon\frac{d}{d\sigma_{ij}} + x\frac{d\psi}{d\sigma_{ij}}, \tag{7}$$

where μ, υ, x are Lagrange multipliers.

Solving a Mathematical Problem for a Smooth Loading Surface

In the case of a smooth loading surface, further specification of the mechanical model is associated with specifying a specific form of the function f, and in the case of a piecewise smooth surface, it is associated with specifying the explicit form of the functions ψ and q. However, the implementation of an experimental program for determining the values of these functions faces significant difficulties associated with the specific strength properties of porous powder composites. A solution to the problem that does not require a specific specification of the type of loading surface is described in [11]. A solution to the problem that requires only knowledge of the dependences of axial and lateral pressures as functions of porosity is described in [12].

To establish the type of boundary conditions, it is necessary to formulate and solve specific problems within the framework of the presented model. The nature of the interactions between the inner surface of the mold‘s working elements and the surface of the pressed body, as well as the geometric features of the pressed blank, must be reflected in these conditions. For a sleeve with an inner radius a, an outer radius b, and a final height h, the type of these conditions is established.

Taking the plane of the lower punch ($z = 0$) as the primary coordinates and assuming it is not deformable, we obtain:

$$\upsilon_z\big|_{z=h} = 0\ . \tag{8}$$

We also assume that the upper punch ($z=h$) is also not deformable.

$$\left.\frac{d\upsilon_z}{dr}\right|_{z=h} = 0. \tag{9}$$

At the same time, it is assumed that, in comparison with the magnitude of the axial deformation of these elements, such deformation is very small and it is elastic.

$$u_r\big|_{r=a} = u_r\big|_{r=b} = 0. \tag{10}$$

In this case, the outer side surfaces of the matrix ($r = b$) and the inner rod ($r = a$) can be classified as friction surfaces. Then, in accordance with Coulomb‘s formula (the law of external friction), we can write

$$\left|\tau_{rz}\right\|_{r=a} = -\lambda\sigma_r\big|_{r=a} \tag{11}$$

$$\left|\tau_{rz}\right\|_{r=b} = \lambda\sigma_r\big|_{r=b} \tag{12}$$

where λ is the coefficient of external friction of the powder with the side walls of the matrix and rod.

Solution of a mathematical problem for a piecewise smooth loading surface

Pressing schemes used in practice are characterized by relative displacement of the outer die and the inner core. Then, mutual contact between iron and cast iron particles can clearly occur.

Taking into account the law of mutual displacement of the above elements allows us to refine relations (11) and (12).

The movement of the press elements in a direction coinciding with the upper punch and not exceeding its displacement in absolute magnitude is consistent with the laws of motion of the press elements used in practice, and therefore this choice of displacement does not limit generality.

At the boundary of the displacement field of the pressed body, the surface area of the displacement matrix of the upper punch is W_1, and that of the matrix itself is W_2.

The displacement components at this boundary have the following equality:

$$|W_2| \le |W_1| \tag{13}$$

$u_z\big|_{r=h}$, which is a function of Z alone and the only non-zero function, will vary continuously from zero on the lower punch to W_1 on the upper one. Due to the absence of discontinuities and large gradients of $u_z\big|_{r=b}$ along z, characteristic of pressing at significant load application rates, it can be assumed that this function is monotonic.

This interpretation of the specific properties of the kinematic field on piecewise-smooth friction surfaces has obvious consequences. Consider the portion of the powder surface moving faster than the outer surface of the die.

In this case, the tangential friction of the powder against the die walls impedes its movement in the direction of the upper punch. For the portion of the powder surface moving slower than the side walls of the die, external friction will facilitate powder movement. The tangential force will be opposite in sign to the case considered above.

Taking into account the above, boundary conditions (11) and (12) can be specified as follows:

$$\tau_{rz}\big|_{r=b} = \begin{cases} \lambda\sigma_r\big|_{r=b} & \text{at} \quad Z_b < Z \le h; \\ 0 & \text{at} \quad Z = Z_b \quad ; \\ -\lambda\sigma_r\big|_{r=b} & \text{at} \quad 0 \le Z \le Z_b; \end{cases} \tag{14}$$

$$\tau_{rz}\big|_{r=a} = \begin{cases} -\lambda\sigma_r\big|_{r=a} & \text{at} \quad Z_a < Z \le h; \\ 0 & \text{at} \quad Z = Z_a; \\ \lambda\sigma_r\big|_{r=a} & \text{at} \quad 0 \le Z \le Z_a; \end{cases} \tag{15}$$

Boundary conditions (8) and (9) are defined using methods that incorporate two independent parameters, z_a and z_b. Both of these parameters, as explained above, characterize the laws of motion of the side press elements. These laws of motion, in turn, determine the pressing pattern. In other words, the proposed method for defining boundary conditions takes into account the pressing pattern [13,14].

In addition to the boundary conditions, it is necessary to consider factors affecting the powder compaction process. When taking pressure into account, this factor is the equality of the average stress on the upper punch. This condition is written as follows:

$$\frac{2}{b^2 - a^2}\int_a^b \sigma_z\big|_{z=h} zdz = \rho \tag{16}$$

When pressing to the stop, the amount of movement of the upper punch should be equal to the amount of displacement of the upper powder layer

$$u_z\big|_{z=h} = W_1 \tag{17}$$

Specifying conditions (16) and (17) requires the values P and W_1. In practice, these values are unknown, so they are determined by solving the problem. In this case, the final average porosity serves as the specified value. It characterizes the final result of the pressing process and is expressed as follows:

$$\theta_{avg} = \frac{2}{h\left(b^2 - a^2\right)}\int_0^h\int_a^b \theta_r drdz \tag{18}$$

where θ_{avg} – is the average porosity after pressing.

Under the given conditions (8)–(10), (14), (15) and (18), by solving equations (14), (15) and (18) and determining the distribution of all unknown quantities (including τ_{rz} and u_z), we find the values of P and W_1.

In connection with the above, it can be stated that when solving the stated mathematical problem, the technological problem for the product pressed according to the specified scheme is simultaneously solved according to the final average porosity and dimensions; it is possible to determine the required pressing force, the stroke of the punch and the distribution of residual porosity.

However, the above-mentioned research method is applicable to axisymmetric components with height transitions. For this purpose, boundary conditions in accordance with (15) are specified on the surface portions parallel to the base, and conditions in accordance with (7) and (14) are specified on the base surface. The lateral surfaces are characterized by conditions (19) and (20).

Verification of the developed model's reproducibility

When forming bushings with a large height-to-wall-thickness ratio, the influence of the pressing pattern on the pressure, the kinematics of the mold elements, and the distribution of average porosity across the cross-section and height of the product is of great importance. Let's consider the four most commonly used pressing patterns: 1 – single-sided; 2 –double-sided; 3 – with counter-moving die and core; 4 – with a floating die and fixed core. The following dimensions were pressed: $h = 50$ mm, R_{out}=24 mm, r_{int}=10 mm.

Each of the above pressing schemes is characterized by two independent parameters: 1) z_a=0, z_b=0; 2) z_a= $h/2$, z_b= $h/2$; 3) z_a=0, z_b= h; 4) z_a=0, z_b= $h/2$.

The main characteristics of the sleeve manufactured using one of the pressing schemes are: a) the values of z_a and z_b; b) the analytical form of the porosity distribution – $\theta(z)$= +$d_1(z)$; c) the values of maximum and minimum porosity – $\underline{\theta}_1(z)_{max}$, $\underline{\theta}_1(z)_{min}$; d) the deviation of porosity– $\theta = \underline{\theta}_1(z)_{max}$–

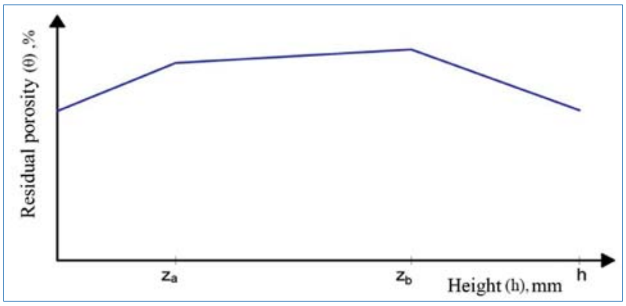

Fig. 2. Distribution of residual porosity (θ) by height (h) of the compaction for arbitrary z_a and z_b (P=700 MPa)

$\theta_1(z)_{\min}$; e) the values of pressure on the lower and upper punches. Using these parameters, it is possible to construct the distribution of porosity by height for arbitrary z_a and z_b for one-sided pressing (**Fig. 2**) and the porosity by height for different pressing schemes (**Fig. 3**).

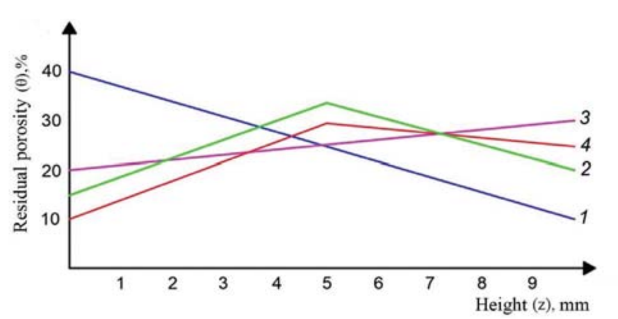

Fig. 3. Distribution of residual porosity (θ) by height (z) of pressing for pressing schemes (P=700 MPa): *1* – one-sided; *2* – two-sided; *3* – with counter movement of the matrix and rod; *4* – with a floating matrix and a fixed rod.

It can be argued that the obtained results provide a fairly comprehensive qualitative picture of the pressing process of iron-cast iron composite for bushing-type parts. However, the resulting models do not fully reflect the pressing process of more complex shapes.

It should be emphasized that the presented calculated data on the residual porosity distribution are in qualitative agreement with the experimental data obtained during the pressing of bushings made of an iron-cast iron composite mixture using various schemes (Fig. 3). In particular, the developed model correctly reflects the influence of the pressing scheme on the unevenness of the porosity distribution along the product height, which is in good agreement with the results of the experimental verification (see Fig. 3) at a constant pressing pressure (700 MPa). This confirms the adequacy of the adopted assumptions and the applicability of the model by verifying the calculated data with the results of the experiments (Figs. 2 and 3). Thus, the proposed model can be used for engineering calculations at the design stage of the technological process. Since the composition under consideration consists of two components of different nature, the assessment of its rheological characteristics during flow in a closed press mold requires a separate approach and is not possible within the scope of this article.

Discussion of the obtained data from the mathematical model

The fundamental principles for constructing a mathematical model for the deformation of powder composite materials with different structural organizations are formulated, and the conditions necessary for describing various structure types are determined. A closed system of governing equations is constructed, incorporating basic conservation laws and taking into account the rheological characteristics of elastic-plastic media (iron and cast iron), enabling a complete compaction analysis taking into account failure conditions. Based on this concept, a mathematical compaction model is formulated for analyzing the elastic-plastic deformation of powder composite materials with different structure types (15–17).

Using mathematical modeling of the compaction process for sleeve-type powder products, it was established that, along with a reduction in axial and radial compaction pressure, additional radial flow of iron powder also occurs, affecting the final density distribution.

The results of mathematical modeling of the compaction of compressible materials can be used to optimize cold and warm pressing processes by creating an initial temperature gradient in the compacted powder (during warm pressing).

Boundary conditions characterizing the interaction conditions between the pressing surfaces of elements and the workpieces are determined. These conditions can be formulated in terms of both speeds and stresses, and in the quasistatic case, relative to the current deformation moment. It is established that for quasi-static processes, initial values of hardening and porosity should be specified, while in the case of dynamic processes, the initial stress and speed [18, 19] must be added to these.

The results of this work have been tested in the production of special sleeve-type powder products made from composite powder mixtures. During the initial pressing stage, iron and cast iron powders are effectively displaced, while the compaction pressure is low. A significant change in the volume of the powder mixture in the matrix is achieved by the displacement of iron powder particles. As the compaction pressure increases, plastic deformation intensifies at the particle contacts, the oxide film on the surface of the interacting particles is destroyed, and sometimes fusion (cold welding) of the plastic particles occurs. However, despite effective plastic deformation, unoccupied volume remains between the particles in the compacted body, which creates the porosity of the workpiece. At the end of compaction, a certain volume in the matrix remains unfilled with powder. Further compaction is hampered by the interlocking of the powder particles and their strain hardening. Cold welding (fusion of the powder particles), which occurs at the boundaries of the iron particles, provides some strength to the component. At excessively high compaction pressures, the deformation resistance is close to that of compact materials [20].

After pressing, the green iron-cast iron mass in the die is relieved only in the axial direction. Even if the load is completely removed, radial stresses still exist between the green compact and the die. A small amount of process lubricant improves the sliding of the particles relative to each other and increases the compaction density. A large amount of lubricant hinders particle compression due to its own poor compressibility and the additional volume it fills.

All of the above parameters and aspects of the pressing process require careful consideration in mathematical modeling of powder compaction and can be useful in the development and design of mold designs. Rational and accurate calculations of the kinematics of the mold‘s working elements, the actual compaction pressure, tool loads, mold design, density distribution, and residual stresses in the mold body, as well as crack prevention, can successfully replace trial and error. However, a number of issues complicate the implementation of a reliable analytical calculation procedure. Primarily, this relates to the selection of a rheological model for the iron-cast iron composite.

The assumption of quasi-isotropy of the material adopted in this study is valid for cold pressing of powder composites under quasi-static loading, where texture formation and pronounced structural anisotropy are limited. To evaluate the pressing process of complex-shaped parts, as well as in the presence of significant density and strain rate gradients, further development of the model is required, taking into account anisotropic effects and the heterogeneity of the rheological properties of the iron-cast iron composite.

Conclusions

1. The following problem can be solved within the framework of the proposed continuum mechanics model: given the required final dimensions of the sleeve, its final volume-averaged porosity, and a given pressing scheme, calculate the distribution of residual porosity (8–40 %) and stresses under external friction (20–100 MPa) of the powder against the die wall during pressing of a cast iron composite.

2. The solution to the boundary value problem for the cold pressing process is independent of the type of loading surface. It is determined by the dependence of axial and lateral pressure on porosity.

3. It has been established that after compaction, the cast iron compact in a rigid die is unloaded only in the axial direction. Even when the pressing pressure is completely removed, some radial stresses exist between the green blank and the die.

4. With a minimal amount of process lubricant in the charge, the compaction of the powder particles improves, and consequently, the compaction density of the pressed part increases. Using a large amount of lubricant degrades the compaction of the particles due to the inherent poor compressibility of the lubricant itself.

5. The results of this study have found practical application in the manufacture of sleeve-type powder products made from composite powder mixtures such as iron and cast iron. It has been established that at high pressing pressures, a sufficiently high compaction density (7.0–7.2) is achieved only due to the high plasticity of the iron particles and the low lateral pressure of the cast iron particles against the die wall.

6. The developed model can be used as a baseline for further development of numerical calculation methods for the pressing of complex-shaped parts.

Financing

This work was carried out with the financial support of the Science Foundation of Azerbaijan – Grant No. AEF-MGC-2024-2 (50)-16/01/1-M-01.

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