Розроблено аналітичну модель напружено-деформованого стану двошарового порошкового сердечнику у металевій оболонці в осередку деформації при виготовленні композиційного матеріалу методом прокатки. На основі розробленої математичної моделі виконано теоретичний аналіз впливу вихідних параметрів на протікання процесу прокатки композиційного матеріалу. З використанням методу скінчених елементів проведено моделювання процесу прокатки різнорідних порошків у металевій оболонці. У результаті проведеного теоретичного дослідження встановлено вплив матеріалу та товщини оболонки на геометричні характеристики осередку деформації, а також впливу коефіцієнту асиметрії на зміну зони пластичного формозмінення та щільності порошкового матеріалу. Визначено розподіли нормальних контактних напружень та відносної щільності вздовж осередку деформації при різних обтисках. Проведено розрахунок складових зусиль прокатки при деформації порошкового сердечнику та металевої оболонки. Встановлено, що зі збільшенням товщини оболонки зростають енергосилові параметри процесу. При цьому складова сили прокатки від деформації оболонки може бути як порівняна зі складовою від деформації порошкового сердечнику, так і перевищувати її у декілька разів. Проведено експериментальні дослідження процесу, які підтвердили правомірність розробленої математичної моделі, яка може бути використана для визначення оптимальних технологічних режимів двошарового порошкового сердечнику у металевій оболонці. Запропоновано технологію прокатки двошарового порошкового сердечнику у металевій оболонці, що включає прокатку за два проходи з поступовим засипанням компонентів у металеву оболонку. Встановлено, що при прокатці за запропонованою технологією відносна щільність сердечнику підвищується при однакових режимах прокатки. При цьому зберігається розмір фракції порошку, що є необхідною умовою для данної технології виробництва

Ключові слова: порошкова металургія, порошкова стрічка, порошок, математична модель, напружено-деформований стан

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STUDY INTO THE ROLLING OF A DOUBLE-LAYERED POWDERED CORE IN A METALLIC SHEATH

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1. Introduction

The issues of energy efficiency, saving material resources, and the use of recycled materials render relevance to the development of powder metallurgy processes that employ pressure treatment methods. Application of powdered materials makes it possible to obtain products with a unique combination of operational characteristics, which are widely used in various industries, specifically in welding and metallurgical production. Powdered tapes are a compacted powdered core in a metal sheath whose air-tightness is ensured by means of a lock connection. The articles produced from powdered materials by using such continuous technologies as rolling and drawing have a number of advantages and are characterized by high efficiency.

Standards for the powdered tape, wires for welding and surfacing govern, in addition to geometric characteristics, a fill factor distribution along the length of a billet, the absence of sheath punctures, as well as ensuring the non-spillage of powder when welding and transportation. Recommendations to ensure qualitative indicators in the manufacture of powdered tapes are empirical in nature at present and are based on the generalization of industrial practice. Application of a wide range of materials for both a sheath and a powdered core requires many industrial experiments on manufacturing this kind of products.

A mathematical apparatus enables the prediction of parameters for the technological process, as well as quality of obtained products, as the stage of design of equipment and technology. Theoretical research on powdered materials treatment pressure is rather well documented. Based on employing various conditions of porous bodies plasticity, the patterns in the formation of density and the strained-deformed state have been quite accurately described. However, the process of deformation of a solely powder medium has not been addressed, while the presence of sheath of a specific shape, size, and with particular properties, changes the mechanism of plastic deformation. As a result, existing calculation methods yield inflated results on the density of a powdered core and the energy-force parameters of manufacturing processes. This leads to a decrease in the operating characteristics of finished products and increases the cost of production and equipment; that predetermines the relevance of the present work.

2. Literature review and problem statement

Existing studies, based on the construction of theoretical models that employ experimental data make it possible to estimate the deformability of cladded dissimilar metals in the process of cold rolling, which has a number of advantages such as dimensional accuracy. The model, presented in [1], is based on a finite element method and enables determining a possibility of destruction for cladded metals with different properties. Another theoretical model, based on a flat cross-section method, was constructed in [2]; it makes it possible to analyze the asymmetric rolling of double-layer sheets. A special feature of the proposed model is a description of the equations of equilibrium of stress fields for each individual layer in the packet. The authors also investigated the curvature of a strip, when it leaves rollers, depending on different rolling conditions that allowed them to devise recommendations for minimizing the curvature of a strip when it leaves the roller gap. A possibility to reduce the resulting curvature of sheets was established, by controlling different sources of asymmetry in rolling. However, the process was considered for dissimilar metals, that is, for continuous materials, which prevents the application of reported calculations when rolling a porous powder medium.

The analytical solutions from [3] were derived based on the modified plate method for asymmetric cladding of sheets fastened before the process of rolling. The proposed calculation procedure provides a more accurate prediction of the distribution of stress fields in layers. The result of calculation demonstrated that increasing the ratio of shear stress or friction coefficients leads to the growth of specific rolling pressure, while the ratio of radii of rollers does not significantly affect the specific shear stress in the zone of contact between layers. The drawback of the study is that it addressed the impact of asymmetry in the rolling process on the formation of the stressed-strained field at a deformation site only for multilayer continuous media. The presence of two layers of the powdered material with different densities, and often with different physical-mechanical properties, at a deformation site changes the pattern of deformation.

Paper [4] proposed a regression model that enables the prediction of basic process parameters at electro-plating of stainless steels. The authors investigated the influence of thickness of each layer, a wire diameter, a wire feed speed, as well as the duration of an electric current pulse, on the quality of cladding. The disadvantage of the proposed study is the complexity of application of the regression model for a wide range of materials, which significantly reduces its effectiveness.

Work [5] examined a CAR (continual annealing and roll-bonding) process, which implies applying a coating made from a powdered material during continuous annealing in rollers; it was established that an increase in runs reduces the drawing of a billet and improves the microstructure of sheets. Data from this study indicate the need to account for all components of the rolled strip affecting the stressed-strained state. However, the study is purely experimental. There is no construction of the mathematical apparatus, which would make it possible to take scientifically substantiated decisions about the selection of technological parameters.

The effect of friction, feed force on the distribution of material porosity over the cross-section of a workpiece was established. Paper [6] built a mathematical model of the rolling process of a powdered material in a sheath, based on the numerical recurrent solution to a finite-difference form of the condition for static equilibrium in the selected elementary volume of a metal. The special feature of a given model is taking into consideration the plastic deformation of a metal sheath at a deformation site. However, a given model is suitable for the rolling processes of composite materials containing a core from a single layer of powder. The presence of multiple layers of powdered materials with different physical-mechanical properties significantly affect the pattern of deformation, which must be taken into consideration when constructing a mathematical model.

Despite a series of studies considered above, which address the rolling process of powdered materials, the effect of the elastic deformation of a metal sheath on energy-force parameters of the process was disregarded. That is connected to the need to simplify calculations and to reduce the bulkiness of mathematical expressions, which is justified by sufficient convergence between the estimated and experimental results from the above studies into the rolling of certain materials. Regularities in the distribution of stress fields at a deformation site and in the changes of technological parameters for the cladding process by a cold-rolling method for sheet steels have been investigated in detail. However, the presence of a powder medium at a thermodeformation site significantly affects a change in the pattern of the stressed-deformed state of a composite material. The above demonstrates the expediency of conducting further studies aimed at quantitative refinement and qualitative extension of results from mathematical modeling. That will ensure a greater degree of scientific validity for those specific practical recommendations that are adopted in each individual case.

3. The aim and objectives of the study

The aim of this work is to study the stressed-strained state at a deformation site when rolling a double-layer powdered core in a metal sheath. This will make it possible to devise practical recommendations for choosing starting materials and rolling modes for multilayer powdered materials in a metal sheath, as well as to improve the efficiency and performance of the rolling process.

To accomplish the aim, the following tasks have been set:

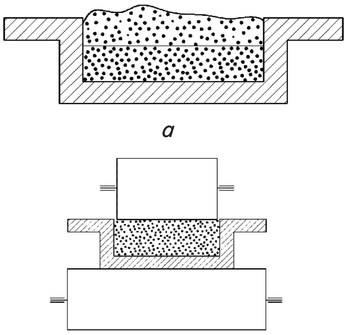
– to construct a numerical analytical model for the calculation of the stressed-strained state of a two-layered powdered core in a metal sheath at a deformation site;

– to carry out a finite-element modelling of the rolling process involving a two-layered powdered core in a metal sheath;

– to study experimentally the rolling process of a double-layered powdered core in a metal sheath in order to validate adequacy of the constructed mathematical model.

4. Construction of a numerical mathematical model of the stressed-strained state when rolling a composite tape

Underlying the built mathematical model of the stressed-strained state when implementing the processes of rolling a two-layered powdered tape in an open U-shaped metal sheath is the approach based on the joint numerical recurrent solution to the static equilibrium conditions and conditions of plasticity for a monometal of the sheath and powdered core [5]. The estimation scheme included two layers of a powder composition: the lower layer, preliminary compacted; the upper layer – bulk (this division is conditional and is introduced to account for different physical-mechanical properties of powdered media) (Fig. 1).


a

b

Fig. 1. Schematic of rolling the two layers of powder in a metal sheath of box cross-section: *a* — secondary filling with a layer of charge; *b* — powder compaction

The estimation scheme, employed in this case, for the integral deformation site is shown in Fig. 2. A given estimation scheme for the integral deformation site includes a compaction zone L_{pl} and a zone of the subsequent elastic recovery L_r.

From the viewpoint of kinematic relationships, the compaction zone was in turn divided into the lagging zones L_{om1}, L_{om2} and the advance zones L_{on1} L_{on2} Given a possibility for the existence of kinematic or geometric asymmetry of the rolling process, lengths of the specified zones on the upper and lower rollers may differ.

The estimation scheme included two layers of a powdered composition: the lower layer, compacted in advance, and the upper layer, bulk (this division is conditional and is introduced to account for different physical-mechanical properties of powdered media) [7]. The analytical description of the value for strip thickness h_x, length-wise the deformation site, employed a parabolic approximation of contact arcs. In order to determine the thickness of a double-layer composition h_x, length-wise the deformation site, we applied a parabolic approximation of the roller arc [8]:

$$h_x = h_1 + (h_0 - h_1)\left(\frac{x}{L_s}\right)^2, \tag{1}$$

where h_1 is the resulting thickness of the composition; h_0 is the initial thickness of the composition; L_c is the length of a deformation site; x is the current coordinate of cross section.

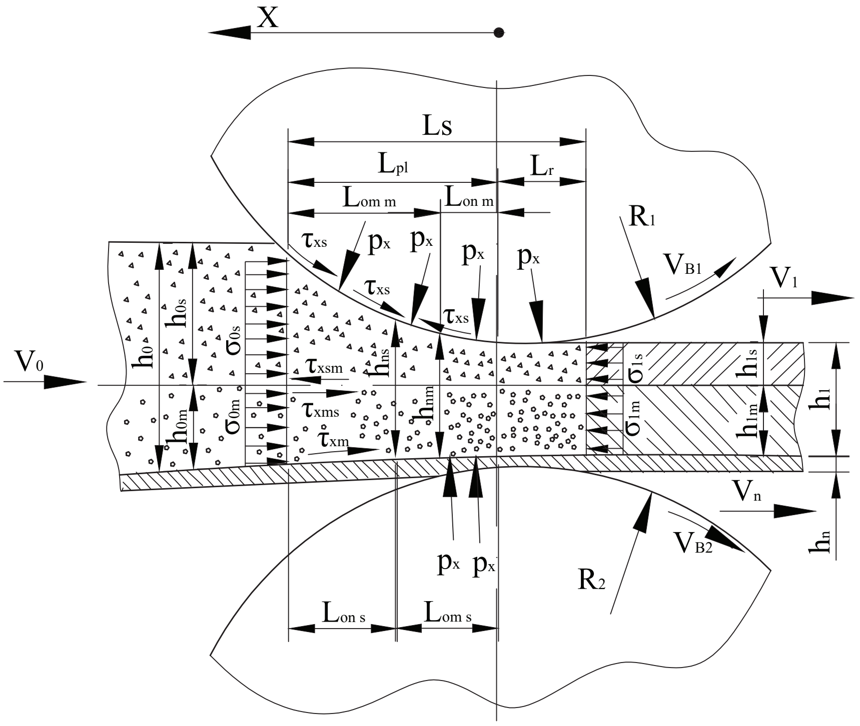


Fig. 2. Estimation scheme of a deformation site in the process of rolling two layers of a powdered material in a metal sheath of box cross-section

The current values for indicators that characterize the friction conditions in a contact zone between the working rollers and a bulk layer of powder $f_{xs} = \tau_{xs}/p_x$ a sheath and the compacted layer $f_{xm} = \tau_{xm}/p_x$, as well as between layers $f_{xsm} = \tau_{xsm}/p_x$ (Fig. 3) [7], were determined with respect to the actual character of their distributions along the length of a deformation site:

– from the side of a lower roller:

$$f_{xm(s)} = \tau_{xm(s)}/p_x = -f_{onm(s)}\left[\frac{L_{onm(s)} - x}{L_{onm(s)}}\right]^{a_{fm(s)}} \tag{2}$$

at $0 < x \le L_{onm(s)}$;

– from the side of an upper roller:

$$f_{xm(s)} = \tau_{xm(s)}/p_x = f_{omm(s)}\left[\frac{x - L_{onm(s)}}{L_{pl} - L_{onm(s)}}\right]^{a_{fm(s)}} \tag{3}$$

at $L_{onm(s)} < x \le L_{pl}$;

$$f_{xm(s)} = \tau_{xm(s)}/p_x = f_{onm(s)}\left[\frac{L_{onm(s)} - x}{L_{onm(s)}}\right]^{a_{fm(s)}} \tag{4}$$

at $0 < x \le L_{onm(s)}$;

– between layers:

$$-f_{xms} = f_{xsm} = -\tau_{xms} / p_x = \tau_{xsm} / p_x = f_{onm}\left[\frac{x}{L_{pl}}\right]^{a_{fms}}, \tag{5}$$

where $f_{omm(s)}$, $f_{onm(s)}$, f_{oms} are the baseline values equal to the values of the respective friction coefficients in a cross section at the input ($x=L_{pl}$) and in a cross section at the output ($x=0$) from the compaction zone; $a_{fm(s)}$, a_{fms} are the power indicators characterizing the shape of a distribution diagram of friction coefficients length-wise of the deformation site ($a_{fm(s)(ms)}=0.2...0.5$) [8]; «s», «m» are the indices, denoting the preliminary compacted and bulk layers of the rolled powdered composition; $L_{onm(s)}$ is the length of advance zones at the contact surfaces of the respective working rollers, linked via a functional description derived from the parabolic approximation and the indicator of a kinematic asymmetry degree of the rolling process $K_v=V_{B1}/V_{B2}$:

$$L_{onm}=\sqrt{\frac{h_1(K_v-1)}{h_0-h_1}+K_v\cdot\left(\frac{L_{ons}}{L_{pl}}\right)^2}. \qquad (6)$$

In addition to those specified above, we adopted, when constructing a mathematical model, a series of the following key assumptions:

– deformation of a powdered strip is two-dimensional and stable over time, in this case, the kinematics of the flow of each powdered layer obey the hypothesis of flat cross sections;

– boundary cross sections of compaction and elastic recovery zones are vertical;

– current values for contact angles α_{xsi} and a_{xmi} tangential of intralayer (shear) τ_{xmsi} stresses along the length of each individual i-th selected elementary volume do not change, while changes in normal p_{xi} and tangential τ_{xmi}, τ_{xsi} contact stresses are linear in nature;

– indicators of mechanical properties, normal stresses $\sigma_{xm(s)i1(2)}$ as well as the kinematical parameters of the rolling process change only length-wise of the deformation site, while their magnitude for the thickness of each individual cross section of the examined component remains constant.

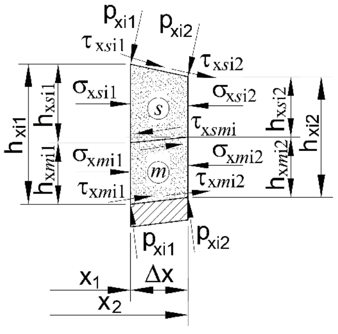


Fig. 3. Estimation scheme of the selected i-th elementary volume when implementing a rolling process of two layers of a powdered material in a metal sheath of box cross section

When modeling the rolling process of a double-layer powdered metal tape in a sheath of box cross section, the entire length of compaction zone L_{pl} was split into K_R elementary volumes, in this case, the geometrical coordinates for each of the i-th individual elementary volume corresponded to:

$$\Delta x_i=L_{pl}/K_R;\quad x_{i2}=x_{i1}-\Delta x. \qquad (7)$$

When rolling a preliminary compacted layer of a powdered material in a metal sheath and a layer of the added charge, velocities of displacement of the strip's components at a deformation site are guaranteed to be equivalent only at cross sections that are close to the output from the deformation site: $V_{1m}=V_{1s}=V_1$. In other cross sections, they will be somewhat different from each other: $V_{xm}\neq V_{xs}$ and $V_{0m}\neq V_{0s}$.

Consequently, the kinematic V_{xmi}, V_{xsi} as well as geometrical h_{xmi}, h_{xsi}, parameters of the rolling process in this case are unknown and must be determined. Known in this case are only the values for the initial thickness of the preliminary compacted h_{0m} and bulk h_{0s} layers. Complete calculation of the stressed-strained state for the i-th selected elementary volume is based on the purposeful sorting of thicknesses h_{xmi2}, h_{xsi2} with respect to the condition of equilibrium for the finite boundary cross section:

$$p_{xi2}=p_{xmi2}=p_{xsi2}. \qquad (8)$$

In order to determine normal contact stresses p_{xi2}, we consider a static equilibrium condition for the elementary volume of a deformation site of a single width, which for the compacted layer takes the following form:

$$\sum F_{xmi}=\sigma_{xmi2}h_{xmi2}-\sigma_{xmi1}h_{xmi1}-\frac{p_{xmi1}f_{xmi1}+p_{xmi2}f_{xmi2}}{2}\Delta x_i-$$
$$-\frac{p_{xmi1}f_{xmsi1}+p_{xmi2}f_{xmsi2}}{2}\Delta x_i+\frac{(p_{xmi1}+p_{xmi2})(h_{xi1}-h_{xi2})}{4}-$$
$$-\frac{(p_{xmi1}+p_{xmi2})(h_{xmi1}-h_{xmi2}-(h_{xi1}-h_{xi2})/2)}{2}=0, \qquad (9)$$

where the accepted positive values for normal stresses σ_x are compressive stresses, and the direction of action of tangential contact $\tau_{xm(s)}$ and intralayer τ_{xms} stresses is taken into consideration via signs in functional descriptions.

In order to determine values for the axial and contact stresses, we employ a condition for plasticity of porous materials for the flat deformed state, implemented in this case [9]:

$$f=\frac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]+$$
$$+\alpha(\sigma_1+\sigma_2+\sigma_3)^2-\beta\sigma_s^2=0, \qquad (10)$$

where $\sigma_1,\sigma_2,\sigma_3$ are the principal stresses acting on the deformed powdered core; α, β are the strain-specific ratios of powder compositions; σ_s is the nominal yield stress of a material forming the base of the powdered material.

According to paper [9], values for coefficients α and β can be determined from:

$$\alpha=a(1-\gamma_x)^m;\quad \beta=\gamma_x^{2n}, \qquad (11)$$

where γ_x is the current value for relative density of a powdered phase:

$$\gamma_x=\rho_x/\rho_0. \qquad (12)$$

Here ρ_x, ρ_0 are the density values of a given powdered composition and its solid phase, respectively; *a, m, n* are the constants defined for each specific composition of a powdered medium, they characterize the dependence of change in α and β coefficients on a change in relative density γ_x.

It should be noted that normal stresses σ_{xmi2} and σ_{xsi2} can be expressed via their respective normal contact stresses p_{xmi2} and p_{xsi2} based on the plasticity condition for loose media, deriving the magnitude of normal stresses σ_x from it:

$$\sigma_{xm(s)i2} = \frac{1-2\alpha_{xm(s)i2}}{1+4\alpha_{xm(s)i2}} p_{xm(s)i2} -$$

$$- \sqrt{p^2_{xm(s)i2}\left[\left(\frac{1-2\alpha_{xm(s)i2}}{1+4\alpha_{xm(s)i2}}\right)^2 - 1\right] + \frac{4}{3}\cdot\frac{1+\alpha_{xm(s)i2}}{1+4\alpha_{xm(s)i2}}\beta_{xm(s)i2}\sigma^2_{sxm(s)i2}}, \quad (13)$$

by substituting it into the equations of static equilibrium, one can determine the normal contact stresses:

$$p_{xm(s)i2} =$$

$$= \frac{\sqrt{t^2_{1m(s)}t^2_{2m(s)} - \left(t^2_{1m(s)} - t_{3m(s)}\right)\left(t^2_{2m(s)} - t_{4m(s)}\right)} - t_{1m(s)}t_{2m(s)}}{t^2_{1m(s)} - t_{3m(s)}}, \quad (14)$$

where, for the compacted layer:

$$t_{1m} = \frac{1-2\alpha_{xmi2}}{1+4\alpha_{xmi2}} h_{xmi2} +$$

$$+\frac{1}{2}\begin{pmatrix}\left(h_{xi1}-h_{xi2}\right) - \frac{1}{2}\left(h_{xi1}-h_{xi2}\right) - \\ -\left(h_{xmi1}-h_{xmi2}\right) - \left(f_{xmi2}+f_{xmsi2}\right)\Delta x_i\end{pmatrix};$$

$$t_{2m} = \frac{1}{2} p_{xmi1}\begin{pmatrix}\left(h_{xi1}-h_{xi2}\right) - \frac{1}{2}\left(h_{xi1}-h_{xi2}\right) - \\ -\left(h_{xmi1}-h_{xmi2}\right) - \left(f_{xmi1}+f_{xmsi1}\right)\Delta x_i\end{pmatrix} - \sigma_{xmi1}h_{xmi1};$$

$$t_{3m} = h^2_{xmi2}\left[\left(\frac{1-2\alpha_{xmi2}}{1+4\alpha_{xmi2}}\right)^2 - 1\right];$$

$$t_{4m} = \frac{4}{3}\cdot\frac{1+\alpha_{xmi2}}{1+4\alpha_{xmi2}}\beta_{xmi2}\sigma^2_{sxmi2}h^2_{xmi2}, \quad (15)$$

for the bulk layer:

$$t_{1s} = \frac{1-2\alpha_{xsi2}}{1+4\alpha_{xsi2}} h_{xsi2} +$$

$$+\frac{1}{2}\begin{pmatrix}\left(h_{xi1}-h_{xi2}\right) - \frac{1}{2}\left(h_{xi1}-h_{xi2}\right) - \\ -\left(h_{xsi1}-h_{xsi2}\right) - \left(f_{xsi2}-f_{xsmi2}\right)\Delta x_i\end{pmatrix};$$

$$t_{2s} = \frac{1}{2} p_{xsi1}\begin{pmatrix}\left(h_{xi1}-h_{xi2}\right) - \frac{1}{2}\left(h_{xi1}-h_{xi2}\right) - \\ -\left(h_{xsi1}-h_{xsi2}\right) - \\ -\left(f_{xsi1}-f_{xsmi1}\right)\Delta x_i\end{pmatrix} - \sigma_{xsi1}h_{xsi1};$$

$$t_{3s} = h^2_{xsi2}\left[\left(\frac{1-2\alpha_{xsi2}}{1+4\alpha_{xsi2}}\right)^2 - 1\right];$$

$$t_{4s} = \frac{4}{3}\cdot\frac{1+\alpha_{xsi2}}{1+4\alpha_{xsi2}}\beta_{xsi2}\sigma^2_{sxsi2}h^2_{xsi2}. \quad (16)$$

As we derived p_{xmi2} and p_{xsi2}, the resulting thickness h_{xsi2} was determined iteratively:

$$h_{xsi2(k+1)} = h_{xsi2k} - A_h \cdot sign\left\{p_{xmi2k} - p_{xsi2k}\right\}, \quad (17)$$

where, at the first cycle of the *k*-th iteration procedure, based on the initial assumption about the equality of extracts, we accepted:

$$h_{xsi2k}\big|_{k=1} = h_{xsi1}h_{xi2} / h_{xi1};$$

A_h is the step of change in layer thickness, the magnitude of which, depending on the degree of approximation to the desired result, was taken to be variable; $sign\left\{p_{xmi2k} - p_{xsi2k}\right\}$ is the gradient assessment of direction in the next increment.

Proceeding to indicators of the stressed-strained state of the *i*-th selected elementary volume for a given case of rolling, the relative deformation of a powdered layer in the longitudinal direction is:

$$\varepsilon_{lxm(s)i2} = \frac{\sigma_{xm(s)i2}\left(1+4\alpha_{xm(s)i2}\right) - p_{xm(s)i2}\left(1-2\alpha_{xm(s)i2}\right)}{p_{xm(s)i2}\left(1+4\alpha_{xm(s)i2}\right) - \sigma_{xm(s)i2}\left(1-2\alpha_{xm(s)i2}\right)} \times$$

$$\times \frac{h_{xm(s)i1} - h_{xm(s)i2}}{h_{xm(s)i1}}, \quad (18)$$

and, based on the condition for mass preservation, resultant within a given volume, the value for relative density of a powdered medium can be determined from:

$$\gamma_{xm(s)i2} = \frac{\gamma_{xm(s)i1}h_{xm(s)i1}}{h_{xm(s)i2}\left(1+\varepsilon_{lxm(s)i2}\right)}. \quad (19)$$

The considered dependences, along with iterative procedures for determining the extent of a deformation site, an elastic recovery zone, and deriving the integral characteristics of the process, produced a complete algorithm for calculating the stressed-strained state when rolling double-layered powdered tapes. The example of calculation results is the estimation distributions of thicknesses and relative densities of layers along the length of a deformation site, presented in Fig. 4.

We also present the distributions of relative densities of layers and the rolling force depending on compression (Fig. 5), as well as the estimated distributions of local energy-force parameters of the process (Fig. 6).

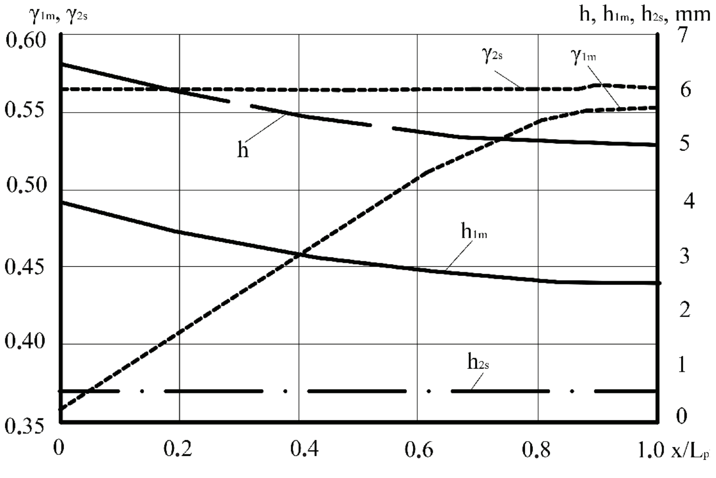


Fig. 4. The estimated distribution of thicknesses and relative densities of the layers and tape along the length of a deformation site in the process of rolling two layers of powdered tape in a metal sheath

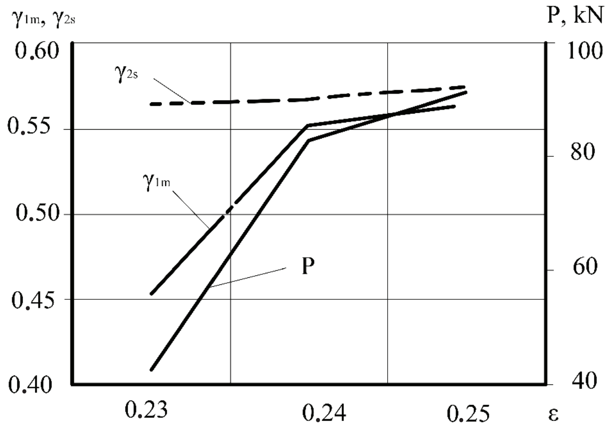


Fig. 5. Estimated distribution of relative densities of layers and the rolling force depending on the compression process of rolling two layers of powdered tape in a metal sheath

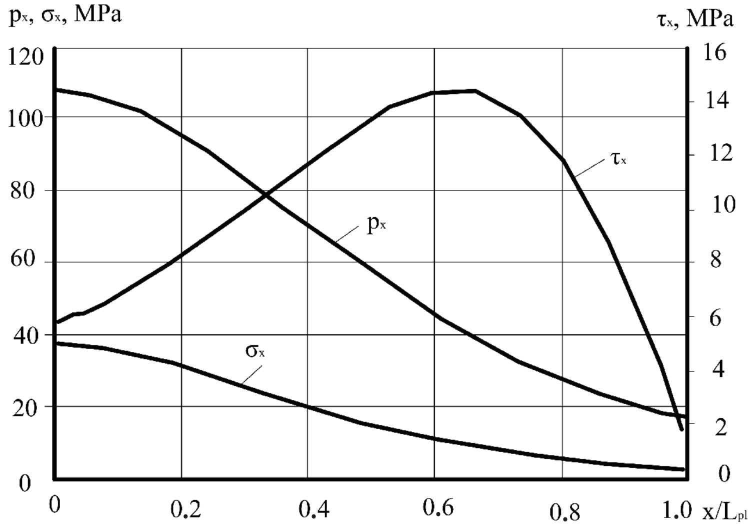


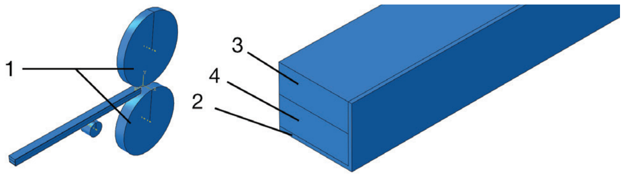
Fig. 6. Estimated distribution of normal, tangent, and normal contact stresses along the length of a deformation site when rolling a powdered electrode tape

Calculations were performed for rolling an iron powder of brand PZhRZ with a relative density of 0.365, and a layer of copper powder with a relative density of 0.565 in the rollers with a diameter of 260 mm at rolling speed 0.03 m/s (thickness of the first layer is 4 mm, second – 2.5 mm).

5. Construction of a finite-element model of the stressed-strained state when rolling a composite material

In order to determine the stressed-strained state at a deformation site at rolling, a description of the mechanical and physical properties of a powdered material is required [10]. The finite-element simulation of the processes of rolling a powdered tape was conducted using the Abaqus CAE software system. The estimation scheme, employed in this case, is shown in Fig. 7: it included the undeformed working rollers and a metallic sheath that is deformed in line with the properties of the continuous medium. The scheme also includes a bulk powdered layer, deformed in line with the properties of a porous medium, and a preliminary compacted powdered layer that is deformed in line with the properties of a porous medium. For the billet, we performed volume discretization (construction of a finite element grid) into elementary regions (finite elements). To simulate the rollers, we employed three-dimensional non-deformable elements.

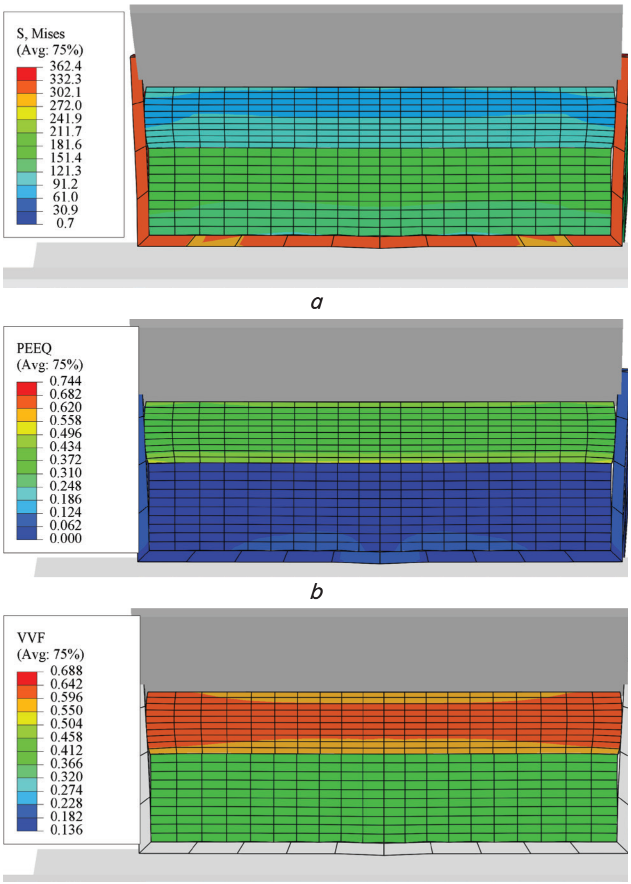
In order to simulate both the powdered core and metallic sheath, we applied the eight-node linear, solid-state reduced elements with destruction control C3D8R. When modeling, the following boundary conditions were assigned: rollers had one rotary degree of freedom and the angular velocity of rotation equal to 1 rad/s. The contact between the workpiece and the rollers was assigned using the contact model «surface to surface» with a coefficient of friction equal to 0.2. In order to estimate the results obtained, the chosen output parameters were the projections of reactions at control points of rollers in the global coordinate system, as well as deformations and strains at nodes of the finite elements of the workpiece nodes, as well as the distributions of porosity in the core. An analysis of the calculated values for stresses, deformations, and porosity for the cross section of layers in the rolled strip (Fig. 8) revealed that the non-uniformity in the distribution of equivalent stresses did not exceed 17.7 %.



a *b*

Fig. 7. A finite-element model of the process of rolling a two-layered powdered tape: 1 – working rollers; 2 – metallic sheath; 3 – bulk powder layer; 4 – preliminary compacted powder layer; *a* – estimation scheme; *b* – billet

Equivalent deformations in this case do not exceed 18.6 %; porosity of the bulk layer – 8.9 %, of the compacted layer – 3.7 %. The character of change in the stresses and deformations is similar to that when rolling a single-layered powdered tape, that is, we observed an increase in values in the near-contact regions. A lower density of the powdered core was registered along its lateral edges. The results of three dimensional finite-element simulation of the examined processes have confirmed the adequacy of assumptions, accepted for the analytical models, about the uniform distribution of parameters for the width of the tape and the adopted hypothesis on flat cross sections.



a

b

c

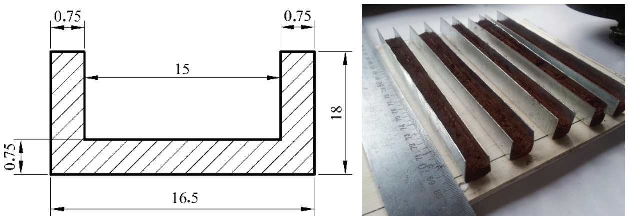
Fig. 8. Distribution of fields when rolling a double-layered powdered tape in a metal sheath: *a* — of equivalent stresses; *b* — of deformations; *c* — of porosity

6. Experimental study into the stressed-strained state of a composite material at a deformation site

Experimental research into the rolling process of powdered tapes was conducted at the laboratory mini bench 100x100 G at AMM Department of Donbass State Engineering Academy (Ukraine). General view of the bench is shown in Fig. 9. Geometrical parameters of billets are shown in Fig. 10; samples after the experiments are demonstrated in Fig. 11. The research was conducted for the case of rolling a copper-based powder and a sheath made from steel 08 kp. Surface of the finished metallic profiles was treated with kerosene prior to filling with a powdered material; a thin layer of silicate glue was then applied to enable a better adhesion between a powdered component and the sheath during rolling. Working rollers were carefully cleaned and degreased before each experiment.

Rolling speed during all experiments was 0.05 m/s, radius of the upper roller is 75 mm, the lower, 50 mm, width of the rolled composition for all cases was 15 mm. Length of the profile, and thus the length of the bulk powder layer was 200 mm, thickness of the metallic sheath was 0.75 mm. The rolling was performed at different clamping in the sheaths of different thicknesses. The study included two series of experiments: rolling a single-layered powdered material, and rolling a loose layer on the preliminary compacted layer in the U-shaped metal sheath. Results of the research into the influence of sheath thickness on energy-force parameters are shown in Fig. 10.

Fig. 9. General view of a working stand at the laboratory mini bench 100x100 G DSEA



a *b*

Fig. 10. Schematic of the U-shaped sheath (*a*) and samples for rolling a powdered tape in a metal sheath (*b*)

It was established that the strength of rolling for a tape with the sheath of thickness 1.2 mm is 2.55 times less than that for a tape with the sheath of thickness 0.42 mm. An analysis of results derived in the course of experiment allows us to draw a conclusion about the influence of sheath thickness on the progress of the rolling process involving powdered materials (Fig. 11, 12).

Fig. 11. Samples of the rolled powdered material in a metal sheath

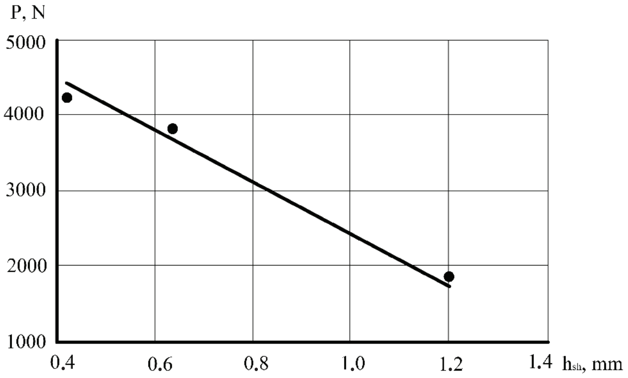


Fig. 12. Experimental dependence of rolling force on sheath thickness

In this case, the larger the thickness of sheath the higher its rigidity and thus the elastic deflection that reduces the length of a deformation site and, consequently, the energy-force parameters of the process, and the deformation of a powdered component. That makes is relevant to account for a given factor in the course of mathematical modeling of the processes of rolling powdered tapes on a metallic substrate and in a metal sheath.

Results of research into the influence of clamping modes when rolling the single-and double-layered powdered materials are given in Table 1. Based on the results of our research, it was found that the values for a rolling force, derived from the theoretical and experimental research, do coincide. In this case, calculation error did not exceed 10 %, which testifies to the reliability of the constructed mathematical apparatus for determining the stressed-strained state parameters of a powdered core at a deformation site when implementing the rolling process.

Table 1

Results of theoretical and experimental research into the rolling of powdered tapes

No. of entry	h_{n0}, mm	h_{n1}, mm	P_{exp}, kN	P_{calc}, kN
1 (rolling in 1 run)	5	3	3.181	3.254
2 (rolling in 1 run)	7.25	6	1.513	1.569
3 (rolling in 2 runs)	4.25→3	3+2→3	14.945	15.452
4 (rolling in 2 runs)	4.25→3	3+5→6	10.604	10.358

It was also established that at rolling based on the proposed technology (in two runs, consistently filling a metal sheath with components), relative density of the core increases under the same rolling modes. In this case, the size of powder fraction is retained, which is a prerequisite for a given production technology.

7. Discussion of results of studying the rolling of a powdered core in a metal sheath

It was established that the rolling of a double-layered powdered tape leads to a significant decrease in the layer of copper powder, while an iron layer's thickness reduces only at the output from a deformation site. This effect is due to that the deformation would occur to the layer with a less resistance to deformation, and the joint deformation of both layers would begin only when their properties become equivalent. The total thickness of tape during rolling process intensively decreases along almost the entire length of the deformation site. There is also an intensive growth in the resulting relative density of the less ductile layer of a material, as well as the stabilization of growth at the output from the deformation site of the resulting relative density of the second layer of a powdered composition. A change in the intensity of compaction of the less plastic layer is also linked to that since the moment both layers flow jointly the deformation degree of the less ductile layer reduces. It is obvious that at small clamping density of the first layer will not attain the density of the second layer; at larger clamping the second layer begins to deform and, eventually, both layers have different density. This demonstrates the feasibility of solving the optimization problems on choosing the clamping modes based on a criterion for reaching the desired density of both layers of a powdered composition. In addition, the distribution of the deformation of layers is affected by the sheath parameters. An increase in the rigidity of a sheath reduces its elastic deformation under the action of a rolling pressure and, as a result, the length of a deformation site. A change in the geometry of a deformation site leads to the redistribution of components of the stressed-strained state and changes the density of layers in a powder composition. Results of the three-dimensional finite-element simulation have confirmed the validity of assumptions, accepted in the analytical models, about the uniform distribution of parameters for width and thickness of a tape within the range of implementation of rolling the relatively thin tapes. Based on our study into manufacturing processes of powdered tapes, a technology has been proposed implying the rolling of a powdered layer, rolling of a double-layered powdered composition, and rolling in a closed sheath of the lock type. Recommendations are given on choosing the loose thicknesses of powdered layers, clamping levels, selection of materials and the sheath thickness depending on the required density of layers and geometrical dimensions of the tape cross section. A given technology makes it possible to obtain the uniform distribution of the cross-section density, and to apply different materials for the core.

8. Conclusions

1. Based on a theoretical analysis of conditions for rolling the powdered materials in open metallic sheaths using a finite-difference method, we have established the effect of shape, material, and thickness of a sheath on geometrical characteristics of the deformation site. It was found that an increase in the sheath rigidity decreases the deformation of a powdered core. It was also established that an increase in the process asymmetry coefficient to 1.15 reduces the region of plastic shape-formation by 10 % while increasing the density of the powder by 5 %. When rolling the double-layered powdered compositions, only the bulk powder layer is deformed, and an increase in clamping at cross sections, close to the output from a deformation site, the pre-compacted layer undergoes deformation as well.

2. Based on a theoretical analysis of rolling conditions for powdered materials in closed metal sheaths of the lock type using a finite-difference method, we have established the

effect of a material and thickness of a sheath on geometrical characteristics of deformation site. It was found that an increase in clamping up to 60 % leads to the deformation of a sheath and disrupts its shape.

3. Based on a theoretical analysis of the rolling processes of powdered tapes in a metal sheath using a three-dimensional finite-element simulation, we have determined that the distribution non-uniformity of equivalent stresses over the cross-section of a workpiece did not exceed 17.7 %, of equivalent deformations – 18.6 %, of porosity of the powdered core – 13.1 %. In this case, an increase in the level of stresses and deformations was observed in the near-contact layers of a powdered core. An increase in porosity occurred in the region of edges; the region of uneven distribution took not more than 25 % of the total area. This testifies to the adequacy of assumptions, adopted in the analytical models, about the non-uniform distribution of parameters across the width of the tape.

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