Theoretical and experimental research on pressing process of porous bodies made of MR wire material

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Abstract. The article represents the main principles of the theory of pressing process of products made of MR fiber material. It is showed that the equations of ideal (excluding external frictional force) pressing process of products made of MR material are represented as power function of pressing pressure depends on density of porous body. The power function of the hardening of the wire material in compact is determined. It is established that the ideal pressing process contains two stages in the range of relative densities of porous bodies [0.15; 0.7]. The main equation of pressing process of products made of MR is obtained. Experimental proof of hypotheses and assumptions confirmed their validity.

1. Introduction
Elastic porous products made of fiber material are widely used in Russia, which is called “metal rubber” (MR). MR material is a porous metal structure (Figure 1), which is produced by cold pressing process of the workpiece made from intersecting wire spirals.

![Figure 1. Products are made of MR material.](image)

MR material is able to withstand aggressive environments, high and low temperatures, high vacuum, humidity, salty sea fog, radiation, mold fungus, and other adverse external effects for a long time. Such unique capabilities of the MR material lead to a wide scope of products:

- protection of objects from vibration and shock, noise cancelling;
- thermal protection of objects and their elements;
- filtration of different media with fineness of purification: 10-300 microns;
- sealing of fixed joints in structures.
The method of MR producing allows to flexible control of its characteristics, mainly due to the right choice of properties of the wire and the parameters of pressing process. A technological breakthrough in producing of new porous materials with unique properties determined the importance and relevance of theoretical and experimental research of the molding process features of products from such materials. The problem of determining the main equation of pressing process of porous bodies made of MR material is solved in article, so the pressing pressure not only connect with density MR, but also with other physical parameters, including technological parameters of workpiece producing. Considering the summarization of existing results by using the continual representation of porous bodies, as well as on the basis of their general and particular principles of consolidation, the problem is solved experimentally and theoretically [1-14].

2. Equations of ideal pressing process of products made of MR material
First of all, it is necessary to analyze and summarize the main results on pressing process of powder and fiber bodies excluding external frictional force (ideal pressing).

The research of the pressing processes of both powder and fiber bodies is usually carried out in two directions. The first one is based on the application of hypothesis of continuity of porous materials produced by pressing powders or fibers [1, 2]. According to the theory of Y. A. Balshin, the second one is based on the theory of contact phenomena [3, 4] and is related to the consolidation process of individual particles of powder or fibers in a porous body (incomplete consolidation).

The theory of pressing process of fiber body first formulated by Y. G. Dorofeev is based on consideration of the total bend of its fibers [5]. According to the assumptions about the permanence of the distribution of points of contact over the lengths of unit segments, as well as the absence of hardening of the fiber material, Dorofeev offers the equation of pressing process of the fiber in the following form:

$$\sigma_n = K \cdot \sigma_m \cdot \bar{\rho}_k^m,$$

where $\sigma_n$ – the pressing pressure; $K$ – constant coefficient depending on the hypotheses and assumptions in the model, as well as the geometric characteristics of the fiber; $\sigma_m$ – yield stress for fiber material; $\bar{\rho}_k = \rho_k / \rho_i$, $\rho_k$ – the relative and absolute density of the compact respectively; $\rho_i$ – absolute density of the fiber material; $m$ – exponent to be determined.

M. Y. Balshin [3] specified the considered theory for the initial stage of pressing process of fiber bodies $\forall \bar{\rho}_k \in [0.25; 0.35]$. According to the methods of the probability theory, he considered that the length of unit segment is inversely proportional to the relative density $- \bar{\rho}_k^2$. As a result, the obtained contact type equation of pressing process for the initial stage of pressing process of fiber bodies has the similar form to equation (1) for $m = 3$:

$$\sigma_n = K \cdot \sigma_m \cdot \bar{\rho}_k^3 = \sigma_k \cdot \bar{\rho}_k^3,$$

where $\sigma_k = K \cdot \sigma_m$ – critical (contact) pressing stress.

Deepening the analysis of the problems of forming porous bodies, it is necessary to notice that in paper [4] for all realizable densities of powder bodies it was proved that the main equation of pressing process can be interpolated by dependence:

$$\sigma_n = \frac{\sigma_k \cdot \bar{\rho}_k^m \cdot \left(1 - \frac{\bar{\rho}_k^m}{\rho_k^m}\right)}{1 - \rho_k^m}.$$
In the practice of producing fiber bodies, including bodies made of MR material, the relative density \( \rho_3 = \rho_3 / \rho_i \) of the workpieces usually varies from 0.035 to 0.15, and the value \( \rho_3 / \rho_k \) – from 0.1 to 0.25. Therefore values \( \rho_3^m \) and \( (\rho_3 / \rho_k)^m \) with \( m \geq 3 \) acquire amount of the second order of smallness. So, the equation of pressing process of powder bodies (3) can be written in a form \( \sigma_n \approx \sigma_k \cdot \rho_3^m \), similar to the equations of pressing process of fiber bodies (1) and (2).

Therefore, there is a one-to-one correspondence between the pressing processes of porous bodies with different structures, due to common features, such as porosity, elastic-plastic and friction bonds between structural elements (powder granules, wire fibers). This important conclusion allows to equally use the previously obtained results of researches of both fiber and powder bodies while creating the theory of pressing process of products made of MR material.

The initial stage of pressing process of the fiber MR material in the range \( \rho_k \in [0.25; 0.35] \) is characterized by the existence of more elastic deformations of the spiral’s turns. The next, main stage of pressing process of MR \( \rho_k \in [0.35; 0.7] \) differs by sharply increasing plastic deformation of the wire due to its bending. The main stage is accompanied by gradually spreading hardening of the wire material along its entire length in the compact. This phenomenon is not considered in the works of Dorofeev and Balshin.

Taking this into account by analogy with powder bodies can be taken a model of a rigidly hardening body with a yield point \( \sigma_{y} = \sigma_{02} \), where \( \sigma_{02} \) – conventional yield limit (stress at 0.2% strain), since the metal wire MR material has the same hardening characteristics under tensile and compression. Such statement allows to use the calculated data of the relative hardening function contained in paper [4], which depends on the density of the compact of the powder body. Their approximation by the power function with the exponent 0.6 allowed to find the dependence (4) of the MR wire material hardening on the density.

\[
\sigma_k = K_B \cdot \sigma_{02} \cdot \rho_k^{0.6},
\]

where \( K_B \) – constant coefficient considering the influence of MR material parameters.

Transformations of equation (2) for the main stage of pressing process of MR \( \rho_k \in [0.35; 0.7] \), considering the hardening of the wire material:

\[
\sigma_n = K_B \cdot \sigma_{02} \cdot \rho_k^{3.6}.
\]

For the initial stage of ideal pressing process (\( \rho_k < 0.35 \)), the hardening of the wire practically doesn’t occur, and equation (5) is converted to a form similar to (2):

\[
\sigma_n = K \cdot \sigma_{02} \cdot \rho_k^{3}.
\]

The obtained equations (5, 6) don’t consider the influence of external frictional forces on the pressing process, which leads to significant errors in the design of porous bodies made of MR material.

3. The equation of pressing process of products made of MR material considering external friction

It is necessary to analyze main force factors of the process of single-action pressing process of powder and fiber products of a cylindrical shape (Figure 2).
The pressing force $P_n$ consists of the load required to compact the powder or wire, and the external frictional forces $P_T$ when interacting with the mold.

The expression for the elementary frictional force, considering the pressed body as a quasi-continuous body $dP_T$:

$$dP_T = \frac{4 \cdot f \cdot K_b}{D} P(x)dx,$$

where $f$ — coefficient of external friction on the sleeve of the mold; $K_b = \sigma_b(x)/\sigma(x)$ — coefficient of lateral pressure; $\sigma(x)$ — pressing pressure in section $x$; $\sigma_b(x)$ — pressure on the mold wall in cross section $x$; $dx$ — thickness of an elementary ring with a diameter $D$; $P(x) = P_n - P_T(x) = \sigma(x) \cdot \pi \cdot D^2 / 4$ — pressing force in the section $x$; $P_T(x)$ — external frictional force in section $x$; $P_n = \sigma_n \cdot \pi \cdot D^2 / 4$ — pressing force; $\sigma_n$ — average total pressing pressure.

From the analysis of expression (7) it follows that the coefficients of external friction $f$ and lateral pressure $K_b$ are the main factors determining the magnitude of the frictional force $P_T$. Moreover, the frictional force, which differs with the height of the compact $H$ and causes unevenness of the pressing pressure profile (Figure 2, curves 1 and 2), contributes to the appearance of a regular heterogeneity in density of the product over the volume.

Let’s return to the analysis of experimental data on pattern of external frictional coefficients and lateral pressure during pressing process of powder bodies. So, data presented in paper [4] for porous bodies made of iron reduced powder show that multiplication $f \cdot K_b$, hereinafter referred to as frictional complex, in the range of relative densities $\rho_k \in [0.4; 0.85]$ differs $f \cdot K_b \in [0.095; 0.11]$ respectively. Therefore, the average value is $(f \cdot K_b)_{cp} = 0.1025$ with an error of about 7%.

Thus, the one-to-one correspondence of the pressing processes of powder and fiber bodies suggests that the condition $f \cdot K_b = \text{const}$ is common for them. Then, equation (7) can be written in the integral form:
The solution of this equation allows to obtain the expression for the frictional force in the section \( x \): \[ P_f(x) = P_n \cdot \left(1 - e^{-\frac{4f \cdot K_n}{D} (H-x)}\right). \] (9)

Consequently, we obtained for the pressure in the compact section \( x \): \[ \sigma(x) = \frac{\sigma_n \cdot e^{-\frac{4f \cdot K_n}{D} (H-x)}}{\epsilon}. \] (10)

If we take \( x = H \) in the expression (9), and \( x=0 \) in the expression (10), respectively, we will obtain:

- for full frictional force \( P_f \):
  \[ P_f = P_n \cdot \left(1 - e^{-\frac{4f \cdot K_n H}{D}}\right); \] (11)

- for averaged pressure at the bottom of the mold \( \sigma_d \) (Figure 2):
  \[ \sigma_d = \frac{\sigma_n \cdot e^{-\frac{4f \cdot K_n H}{D}}}{\epsilon}; \] (12)

Consider the influence of external friction on the pressing process of products made of MR. The height of the elementary ring \( dx \) (Figure 2) can be expressed with mass characteristics of compact:

\[ dx = \frac{4dM}{\rho(x) \cdot \pi \cdot D^2}, \] (13)

where \( M \) – the mass of the wire in the compact; \( \rho(x) \) – density of the compact in section \( x \).

Mass \( M \) can be expressed considering the parameters of the workpiece and compact:

\[ \rho_3 \cdot H_3 = \rho_k \cdot H, \] (16)

where \( H_3 \) – the height of the cylindrical workpiece with a density \( \rho_3 \).

If we integrate equations (15) with regard to expression (16), we will obtain the equation for the main stage of pressing process of the MR material, considering external friction:

\[ \sigma_n = 1.46 \cdot K_B \cdot \sigma_{02} \cdot \frac{f \cdot K_h \cdot \rho_3 \cdot \Phi_3}{1 - e^{-\frac{1.1f \cdot K_n H}{D}}}; \] (17)
where $\Phi_3 = H_3/D$ – form factor of workpiece.

If we consider expression (6), we will similarly obtain the equation for the initial stage of pressing process of the MR material, considering external friction:

$$
\sigma_n = 2.37 \cdot K \cdot \sigma_{02} \cdot \left\{ \frac{f \cdot K_b \cdot \bar{\rho}_3 \cdot \Phi_3}{1 - e^{-\frac{1.33 \cdot f \cdot K_b \cdot \bar{\rho}_3 \cdot \Phi_3}{\bar{\rho}_k}}} \right\}^3.
$$

(18)

We write in the class of piecewise continuous functions the main equation of pressing process of porous bodies made of MR fiber material at the initial and main stages. If we make the connection of equations (17) and (18) at the point $(\bar{\rho}_k, \sigma_n(\bar{\rho}_k))$. Unknown value of the coefficient $K$ is found from the condition $\bar{\rho}_k = 0.35$:

$$
K = 0.616 \cdot K_B \left( \frac{(1 - e^{-3.8 \cdot f \cdot K_b \cdot \bar{\rho}_3 \cdot \Phi_3})^3}{(1 - e^{-3.17 \cdot f \cdot K_b \cdot \bar{\rho}_3 \cdot \Phi_3})^3} \right) (f \cdot K_b \cdot \bar{\rho}_3 \cdot \Phi_3)^{0.6}.
$$

(19)

The value of the coefficient is determined experimentally using the expression:

$$
K_B^{(e)} = 0.685 \cdot \frac{\sigma_n^{(e)}}{\sigma_{02}} \cdot \left( \frac{1 - e^{-\frac{1.33 \cdot f \cdot K_b \cdot \bar{\rho}_3 \cdot \Phi_3}{\bar{\rho}_k^{(e)}}}}{f \cdot K_b \cdot \bar{\rho}_3 \cdot \Phi_3} \right)^{3.6}.
$$

(20)

where $\sigma_n^{(e)}$ and $\bar{\rho}_k^{(e)}$ – the experimental values of pressing pressure and density, related to theoretical dependence (17).

So, obtaining the correct main equation of pressing process of products made of MR should be indissolubly related to the results of experimental researches. They should confirm the power type of functions at the initial and main stages of pressing process, as well as specify the theoretically obtained values of the exponents $m$. The proof of the hypothesis $f \cdot K_b = \text{const}$ should be carried out and the averaged value of the coefficient $K_B^{(e)}$ should be determined considering the results above.

4. Experimental research on pressing process of MR wire material

The proof of hypothesis $f \cdot K_b = \text{const}$ and determination of its values was based on the calculated dependence (21), obtained from expression (11):

$$
f \cdot K_b = \frac{\bar{\rho}_k^{(e)}}{4 \cdot \bar{\rho}_3^{(e)} \cdot \Phi_3^{(e)}} \ln \left( \frac{P_f^{(e)}}{P_n^{(e)}} \right),
$$

(21)

where $\bar{\rho}_k^{(e)}, \bar{\rho}_3^{(e)}, \Phi_3^{(e)}, P_f^{(e)}, P_n^{(e)}$ – experimental counterpart.

The test results of specimens made of MR material in the density range of interest $\bar{\rho}_k \in \{0.11; 0.7\}$ obtained by processing of the experimental data contained in paper [6] considering expression (21) are presented in figure 3. So, the average value of the friction complex is $(f \cdot K_b)^{cp} = 0.105$, and the coefficient value is $K_B^{(e)} = 2.089$. 
Figure 3. Dependence of the friction complex on the density of a porous body made of MR material.

The results of experimental researches to determine the dependence of the dimensionless pressure of the pressing process $\sigma_n$ on the average density of the compact with different parameters of MR material and mechanical characteristics of the wire material are presented in figure 4.

Figure 4. Researches of the pressing process of porous cylindrical bodies made of MR material.

All the obtained dependencies are characterized by two clearly defined parts (two stages of pressing). The variation range of the exponent $m$ for the initial stage is $[2.42; 2.89]$, and for the main $[3.46; 4.0]$. So, the hypothesis about the hardening of the wire material for the main stage, which is close to the hardening of particles in powder compact, turns out to be true. The decrease of the exponent for the initial stage of pressing process to 2.89 is probably determined by the influence of external frictional forces.

Also, the pressure $\sigma_n$ at other fixed parameters is directly proportional to the value $\sigma_{02}$. These results are in good agreement with theoretical data (5) and (6). Also, the influence on the pressing process of the density of the workpiece is identified (the degree of radial pressing of the workpiece) $\sigma_n = K_p \rho_j^{0.22}$, where $K_p$ – constant coefficient). The influence of the geometrical parameters of the...
wire spirals and the form factor $\Phi_3$ on the character of the pressing processes is within the experimental error.

Finally, summarizing the results of theoretical and experimental researches considering the expressions (17-21), we write the semi-empirical main equation for single-action pressing of porous bodies made of MR material in the following form:

$$\sigma_n = \sigma_{02} \cdot \rho_3^{0.22} \cdot 10^{-3} \left\{ \begin{array}{l}
4.839 \left( \frac{\rho_3 \cdot \Phi_3}{0.133 \rho_k \Phi_k} \right)^3, \quad \forall \rho_k \in [0.11; 0.35]; \\
1.406 \left( \frac{\rho_3 \cdot \Phi_3}{0.111 \rho_k \Phi_k} \right)^{3.6}, \quad \forall \rho_k \in [0.35; 0.7].
\end{array} \right. \quad (22)$$

5. Conclusions
The theory of axisymmetric pressing process of fiber bodies and the obtained main equation of pressing process of MR material (22) can be extended to different types of pressing conditions and product shapes.

So, for two-action pressing of cylindrical products is enough to take $\Phi_3^{(d)} = 0.5 \cdot \Phi_3$.

It is enough to determine the form factor of the workpiece in the case of an arbitrary contour of the lateral surface of a product with an internal cavity:

$$\Phi_3 = \frac{(L_H + L_B) \cdot H_3}{4 \cdot S_n}, \quad (23)$$

where $L_H, L_B$ – geometrical parameters of the outer and inner contours of the cross section of the pressed body; $S_n$ – cross sectional area.

The results of theoretical and experimental researches, as well as their summarization, can serve as a basis for researching volume pressing process of porous bodies made of fiber materials, considering the uneven distribution of density over the volume.

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