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AN ANALYSIS OF MECHANICAL PROPERTIES OF POROUS MATERIAL WITH COILED WIRE

Key words: coiled wire, porous tube, internal and external pressure, strength, stability.

Abstract: This article examines the skeleton structure of a product from porous permeable material based on a wire coil. The product consists of a round, porous, thin-walled tube. Two variants of tube load are considered, i.e. those involving internal and external pressures of a working fluid. Mechanical properties of the material have been analyzed. It has been found that the strength and stiffness of the tube depend on the quality of wire coil bonding, which results from technological parameters.

Analityczne badanie właściwości mechanicznych porowatego materiału z drutu nawijanego

Słowe kluczowe: drut nawijany, rurka porowata, ciśnienie wewnętrzne i zewnętrzne, wytrzymałość, wyboczenie.

Streszczenie: Opisano szkieletową strukturę wyrobu z porowatego przenikalnego materiału na podstawie nawijanego drutu. Wyrób przedstawiony w postaci porowatej okrągłej cienkościennej rurki. Rozpatrywano dwa schematy obciążenia rurki środowiskiem roboczym – ciśnieniem wewnętrznym i zewnętrznym. Zostały analitycznie zbadane właściwości mechaniczne materiału i ustalono, że jego wytrzymałość i sztywność zależą od jakości przyczepności zwojów drutu, które są związane z technologicznymi warunkami produkowania.

Introduction

Effective and long-term operation of many modern devices and machines, involving various appliances for filtering, sound absorption, or temperature control depends on the reliability of such items as filters, noise suppressors, or thermally insulated pipes. The various actions of these components consist in absorbing or displacing working fluids. Such products are usually composed of porous materials (PM) made of powders, fibres, or mesh [1].

Operational properties of PM are connected with their structural characteristics (porosity, size and specific surface and specific surface of the pores) and skeletal characteristics (cohesion and strength of the skeleton element bonds). Most of the known research focuses on structural characteristics and permeability. The reliability of materials, however, also depends on their mechanical properties, which necessitates the testing of their skeletal characteristics. The PM's skeletal structure represents a system of interrelated elementary particles, specifically oriented and consolidated to make up a solid body [1].

Among numerous PMs, the most efficient materials in terms of dynamic permeability and dynamic strength are those using woven and knotted nets [1, 2]. A relatively new PM with a similar structure is referred to as a porous material with coiled wire (CWPM) [3]. Such material is composed of crossed and layered wire wound on a cylindrical holder, subsequently subjected to deformative processing, i.e. radial reduction. This method excludes thermal treatment (sintering), which is essential in the manufacture of powder materials and several fibrous materials. In this way, CWPMs acquire the form of a round, porous, thin-walled tube.

Mechanical properties of CWPMs remain to be extensively examined.

1. Construction of the material skeletal structure

The strength of PMs depends on the strength of the skeletal material, i.e. on the cohesion of elementary particles. In CWPMs, metal bonds between the wire coil turns in places of their contact may not exist, as the technology of manufacturing may not include heat treatment, which is necessary for powder materials. There are, however, mechanical bonds resulting from the mutual adherence of coiled wire turns as follows [3]:

1) During wire coiling, when cross-wound turns of the coil get interwoven, attached to each other at numerous points, and at the same time forming a grid at each wire layer; and,

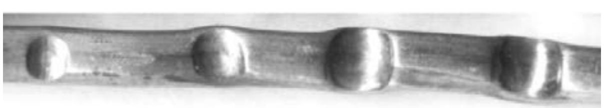

Fig. 1. Indentations at different loads on the wire

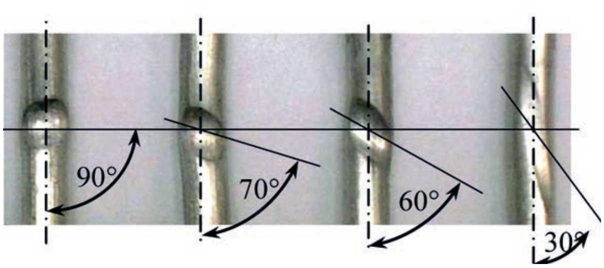

Fig. 2. Shapes of the wire contact surfaces for different angles

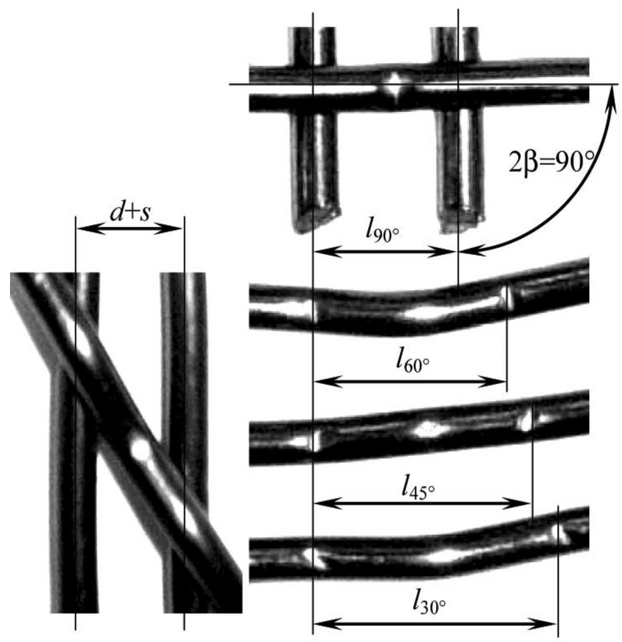

Fig. 3. Deflection of the wire for different angles

2) During radial reduction, when the structure gets tightened by filling the voids between the coil turns of lower layers by plastic contact deformation and the bending of the wire turns.

In addition, increased contact surfaces of the coil turns, i.e. indentations (Fig. 1) that improve mutual wire attachment enhance the mechanical properties of CWPMs. The shape and size of the contact surface areas, apart from deformative treatment pressure, depends on the angle of wire winding. It had been established [3, 4] that, to increase the contact surface areas, one should coil the wire at an angle close to the limit of the possible range of 5° to 45° (Fig. 2). The winding angle is related with wire bending, i.e. the smaller the angle, the longer the section between the contacts, and bigger deflection of the cross wire (Fig. 3). Modelling the interaction and wire deflection was done on samples with larger diameter wire (Fig. 4).

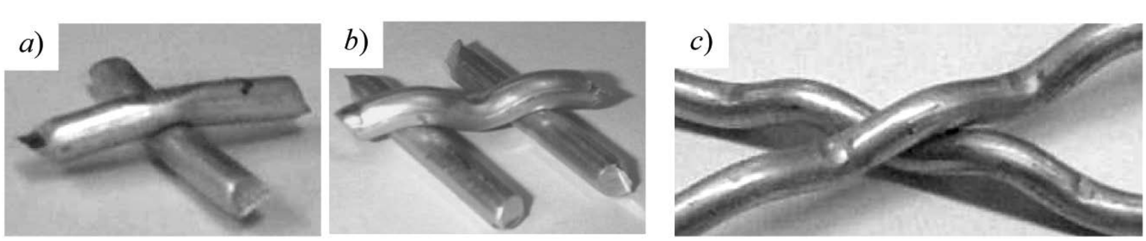

Fig. 4. Modelling of interaction (*a*) and deflection (*b*) of the wire turns by discrete samples, and by wire package samples (*c*)

2. Assessment of material strength and stiffness

While the permeability of PMs decreases the pressure of working fluids, the designer needs to know the critical pressure on the porous wall that, if exceeded, may lead to the material structure deformation or loss of material strength [1]. The working pressure falls due to the penetration of the fluid through the porous structure of the material, and the difference (gradient) of inlet and outlet pressures is the actual pressure that acts on the CWPM skeletal structure:

$$p_{rob}^{wej} - p_{rob}^{wyj} = \Delta p_{rob} = p \tag{1}$$

The pressure gradient depends on the product wall thickness, material structural characteristics and permeability (mainly from porosity, the size and shapes of pores), viscosity, flow rate of the fluid, and thermal conditions, but also on the material's skeletal resistance to fluid pressure [1].

Calculations were made for a porous thin-walled tube with length L and internal diameter D_{opr}, composed of wire with constant diameter d, which is placed in n number of layers at angle β and constant spacing s. The structure is regarded as regular throughout the material volume. Two patterns of tube load are considered, i.e. the pressure acting on the internal and external tube surface (Fig. 5).

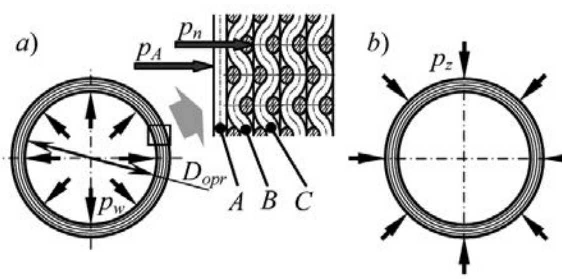

Fig. 5. A diagram of porous tube load by internal (*a*) and external (*b*) pressure

When pressure p_{wew} acts inside the tube (see Fig. 5), there is a risk that the tube may lose its strength due to discontinuities in the skeletal structure or irreversible deformation of the structure, e.g., a wire may be broken at some sections of the coil or the wire bonds may yield. Less strength exists in layer A, where wire turns practically do not change their length in the entire CWPM manufacturing process. The turns of the second layer B, third layer C, and further layers during radial reduction are successively placed on a smaller diameter. The margin of length for bending increases with each layer, which facilitates the bonding of the turns and strengthens the tube wall [5, 6]. Therefore, to prevent wire breakup in the first layer or the "reverse plastic deflection" of further layers, one condition for maintaining the strength of CWPM must be met, i.e. the creation of a load for elastic deformation of the tube.

A model of a porous tube is presented in the form of perforated cylindrical shell, which is formed by a set of wire turns in layer A in a porous bandage of layers of B, C, and further ones. The pressure acting on the skeleton consists of pressure on the first layer p_A and pressures p_n affecting other layers inside the tube wall (see Fig. 5*a*):

$$p_{wew} = p_A + p_n \tag{2}$$

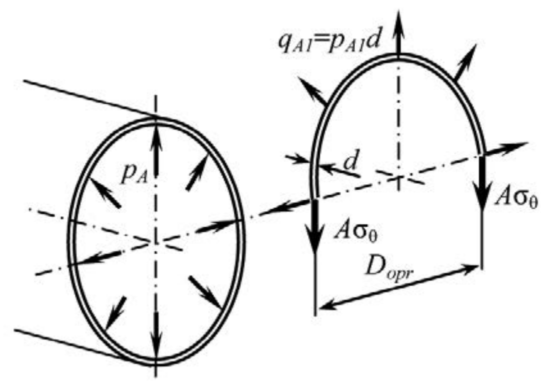

Fig. 6. A diagram for calculating the load on one wire turn in layer *A*

Let us consider a discrete wire turn in layer A that is affected by a uniform load $q_{A1}=p_{A1}d$ (Fig. 6) [7]. In the middle of the turn, an internal tensile force is created, which is caused by tangential stress σ_θ. From the equilibrium condition, we obtain the following:

$$q_{A1} D_{opr} = 2A\sigma_\theta \tag{3}$$

where $A=\pi d^2/4$ – area of the wire cross-section.

The number of turns in layer A of the porous tube is determined as follows [8]:

$$n_A = \frac{2L\cos\beta}{d+s} \tag{4}$$

Then, taking into account Equation (3) and Expression (4), the load in the whole layer A is calculated according to the following formula:

$$q_A = q_{A1} n_A = \frac{\pi d^2 L\cos\beta}{(d+s)D_{opr}} \cdot \sigma_\theta \tag{5}$$

Plastic flow of the wire material occurs after the stress reaches the yield point σ_{pl}; hence, the critical pressure in layer A is equal to the following [7]:

$$p_A^{kr} = \frac{q_A}{d} = \frac{\pi d L\cos\beta}{(d+s)D_{opr}} \cdot \sigma_{pl} \tag{6}$$

In the middle of the porous tube wall, the pressure p_n is distributed onto all the layers and is received by elementary parts of the turns. Each part in any turn of any *i*-th layer can be presented as a beam fixed on both sides (statically indeterminate) with a large curvature whose span length is $l = (d+s)/sin2\beta$ loaded by a force F concentrated in the centre of the deflected span (Fig. 7). The same force is calculated in all passages throughout the tube, because the tube has a thin wall with a regularly organized internal structure. When stresses in the beam reach the yield strength of wire material, wire turn bonds will fail. The structure, therefore, will be disarranged at stresses equal to the following [7, 9]:

$$\sigma_{pl} = \frac{M_{max}}{A(\rho_C - \rho_0)} \cdot \frac{|\rho - \rho_0|}{\rho} = \frac{8M_{max}}{Ad} = \frac{4F(d+s)}{\pi d^3 \sin 2\beta} \qquad (7)$$

where $M_{max}=Fl/8$ – maximum bending moment in the loaded fragment [9]; $\rho_C=d$, $\rho_0 = 0.9d$, and $\rho = 0.5d$ – distances from the curvature axis to, respectively, the centre of gravity, the neutral layer, and the most vulnerable point of the wire cross-section (see Fig. 7).

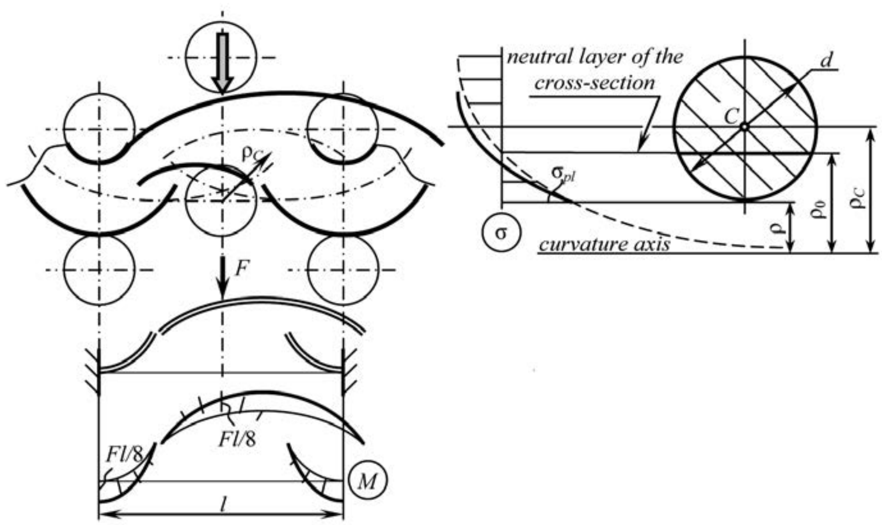

Fig. 7. Schematic diagrams for calculating the load and cross-section of a deflected beam and a graph of bending moments

From Formula (7) we find the bending force as follows:

$$F = \frac{\pi d^3 \sin 2\beta}{4(d+s)} \cdot \sigma_{pl} \qquad (8)$$

The length of wire required for making a tube with length L and thickness h can be expressed as follows [8]:

$$l_d = \frac{2\pi n L(D_{opr} + h)}{d+s} \qquad (9)$$

Then the critical pressure inside the tube wall equals

$$p_n^{kr} = \frac{F}{l_d d} = \frac{d^2 \sin 2\beta}{8nL(D_{opr} + h)} \cdot \sigma_{pl} \qquad (10)$$

An analysis of the expressions (6) and (10) shows that required pressure for breaking the turnsof first layer *A* is greater than the pressure for unmeshing the turns of inner layers (*B*, *C*, and others). So, the pressure inside the tube, disarranging the structure of CWPM, should not exceed the following value:

$$p_{wew}^{kr} = p_n^{kr} = \frac{d^2 \sin 2\beta}{8nL(D_{opr} + h)} \cdot \sigma_{pl} \qquad (11)$$

although the maximum pressure that the tube can withstand is equal to

$$p_{wew}^{max} = p_A^{kr} + p_n^{kr} = \frac{\pi d L \cos\beta}{(d+s)D_{opr}} \cdot \left(1 + \frac{d(d+s)\sin\beta}{4\pi n L^2 (1 + h/D_{opr})}\right) \cdot \sigma_{pl} \qquad (12)$$

When external pressure p_{zew} is created, (Fig. 5b) the tube does not lose its strength, but loses its stability, which practically translates into bending, or wall deflection, while the cross-section shape changes from the stable circular shape to the unstable elliptical shape (Fig. 8). To maintain its stability when affected by outside pressure, the tube can only be affected by elastic deformation. With a given pattern of porous tube loading, all the layers work similarly, and their number, directly related to the thickness of tube wall, provides for adequate stiffness of the tube skeletal structure.

Let us consider a problem of the stability of a ring with diameter D_i, created by one wire turn in *i*-th layer, compressed by radially directed concentrated forces F_i (see Fig. 8). These forces are transmitted from the external layers inwards, creating continuous load

$q_i = 2F_i/D_i$, and when the ring loses stability, the load equals the following [10]:

$$q_i = \frac{36EI}{D_i^3} = \frac{9\pi d^4 E}{16 D_i^3} \tag{13}$$

where
$I = \pi d^4/64$ – moment of inertia of the wire cross-section;
E – Young's modulus of wire material.

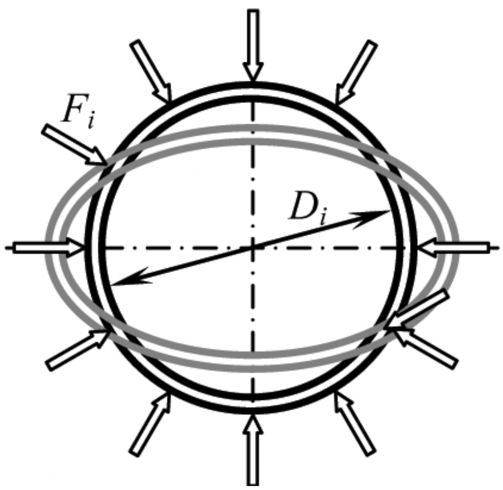

Fig. 8. A diagram for solving a problem of ring stability

Therefore, the critical external pressure causing the tube to crush cannot exceed the following value:

$$p_{zew}^{kr} = \frac{1}{d} \cdot \sum_{i=1}^{n} q_i = \frac{9\pi d^3 E}{16} \cdot \left(\sum_{i=1}^{n} \frac{1}{D_i} \right)^3 = -\frac{E}{\left[n \cdot \frac{D_{opr} + h}{1{,}2d} \right]^3} \tag{14}$$

It has been assumed herein that $\sum D_i = n(D_{opr} + h)$ [8].

The strength and stiffness of a porous tube are higher if the wire used has a higher yield point or larger diameter; whereby, the larger the wire diameter, the greater the difference between the internal and external pressure (Fig. 9). On the other hand, wire with a smaller diameter will increase the number of surface contact areas, i.e. inter-turn meshing, which also strengthens the CWPM skeletal structure [11]. Therefore, the wire diameter should be selected during accurate calculation of PM's flow capacity.

To introduce the dependence of pressure on technological conditions of making CWPM components, the following ranges were determined (Fig. 10): the relative gap between wire turns $n_s = s/d = 1...3$; the angle of wire winding $\beta = 5°...45°$; wall thickness $h = 1...5$ mm; and, the internal diameter of the tube $D_{opr} = 10...50$ mm. It was assumed that $n \le D_{opr}/16d$ [8].

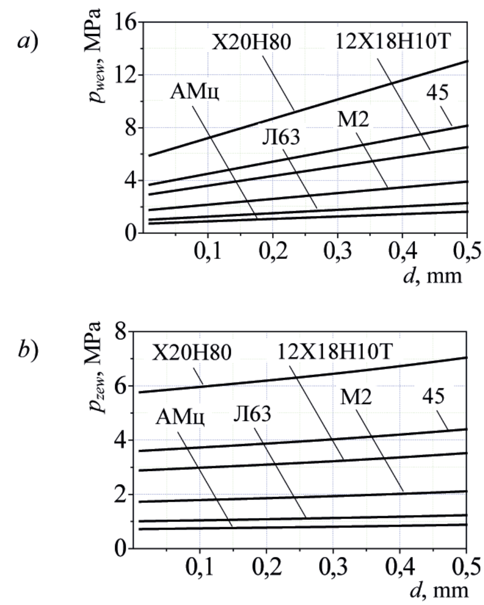

Fig. 9. Dependence of internal (*a*) and external pressure (*b*) in a porous tube on the wire diameter and material

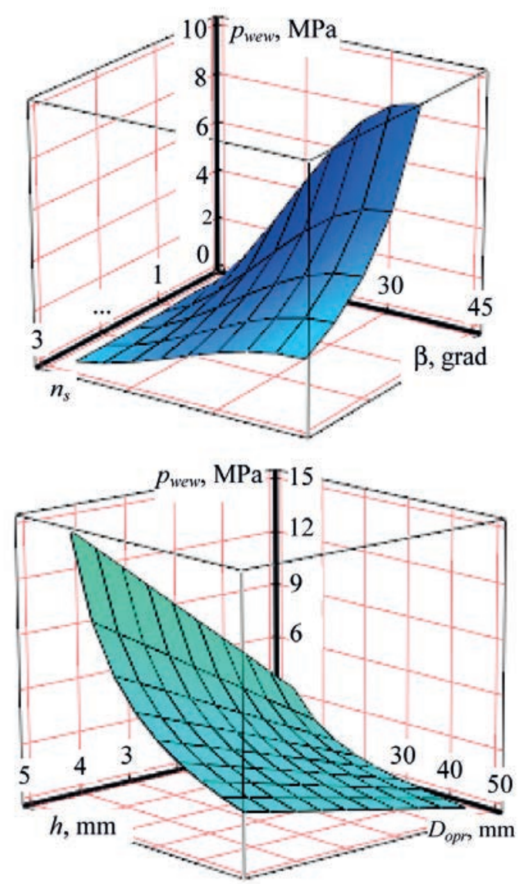

Fig. 10. Surface areas determining the change in internal pressure in the porous tube depending on the technological conditions of production

Conclusions

Mechanical properties of porous materials depend on the strength of their skeletal structures and the cohesion of particles. In CWPMs, metallic bonds between wire turns in places of their contact do not exist, because thermal tretment is not used in their manufacturing. However, owing to the adhesion of wire turns, there are mechanical bonds created through cross-winding of wire and radial reduction. The adhesion of wire turns is improved by increasing the contact areas of the identations. To obtain larger deflections and identations, coiling should be made at a small angle. The structure of material may be considered as organized.

To determine the strength of a tube made of CWPM, we examined uniformly distributed load on the inside surface of the tube, assuming that the critical (destructive) pressure was one at which the tube integrity was lost (wire broken or wire bonds lost). To assess the stability of tube shape, we examined a uniformly distributed load on the external surface, in which case, the critical (crushing) pressure would cause the tube wall deflection, i.e. the tube cross-section would lose its stable circular shape. It was found that the strength and stiffness of a porous tube will be enhanced if the wire used has a larger diameter or higher yield point. It was observed that increasing the wire diameter leads to a larger difference between the internal and external pressures.

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