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ENGINEERING METHODS FOR DETERMINING THE POROSITY IN THE CONICAL PARTS OF SINTERED THIN-WALLED TUBES OF HOT DRAWING AND EXTRUSION

The formula for determining the change rate of porosity of the theory of short-term creep hardening of porous materials is simplified. By the analytical method, the data on the investigation of the stress-strain state of hot drawing and extrusion in a conical matrix of thin-walled nonporous tubes are used. Porosity in different cross sections of conical parts of sintered tubes are determined and the obtained data are analyzed.

Keywords: *sintered thin-walled pipe, porosity, hot drawing and extrusion, short-term creep hardening theory of porous materials, circumferential, meridional and mean stresses.*

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ІНЖЕНЕРНІ МЕТОДИ ВИЗНАЧЕННЯ ПОРИСТОСТІ КОНІЧНОЇ ЧАСТИН СПЕЧЕНИХ ТОНКОСТІННИХ ТРУБ ГАРЯЧОГО ВОЛОЧІННЯ ТА ПРЕСУВАННЯ

Спрощується формула визначення швидкості зміни пористості теорії зміцнення короткочасної повзучості пористих матеріалів. Використовуються дані дослідження аналітичним методом напружено-деформованого стану процесів гарячого волочіння та пресування тонкостінних безпористих труб конічної матриці. Визначаються пористості в різних поперечних перерізах конічних частин спечених труб і аналізуються отримані дані.

Ключові слова: *спеченна тонкостінна труба, пористість, гаряче волочіння та пресування, теорія зміцнення короткочасної повзучості пористих матеріалів, окружне, меридіальне і середнє напруження.*

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ИНЖЕНЕРНЫЙ МЕТОД ОПРЕДЕЛЕНИЯ ПОРИСТОСТИ В КОНИЧЕСКИХ ЧАСТЯХ СПЕЧЕННЫХ ТОНКОСТЕННЫХ ТРУБ ПРИ ГОРЯЧЕМ ВОЛОЧЕНИИ И ПРЕССОВАНИИ

Упрощается формула определения скорости изменения пористости теории упрочнения кратковременной ползучести пористых материалов. Используются данные исследования аналитическим методом напряженно-деформированного состояния процессов горячего волочения и прессования тонкостенных беспористых труб в конической матрице. Определяются пористости в различных поперечных сечениях конических частей спеченных труб и анализируются полученные данные.

Ключевые слова: *спеченная тонкостенная труба, пористость, горячее волочение и прессование, теория упрочнения кратковременной ползучести пористых материалов, окружное, меридиональное и среднее напряжения.*

The solution of technological problems of solid material hot processing at high deformations is based on the classical equations of short-term creep of metals [1] and the results of the difficult to implement experimental studies at high temperatures, as a result of which the equation of the material state is worked out: the formula of the dependence equivalent stress σ_{eq} on the equivalent rate of deformation ξ_{eq}, the deformation temperature T and the parameters characterizing the properties of the material. Taking into account short-term creep of solid materials in [1], numerous technological problems of hot working are solved.

Paper [2] is based on the classical theory of creep, in which, using the formulae of the plasticity theory of porous materials [3], the version of the theory of short-term creep hardening of porous materials (TS-TCHPM) is obtained, where besides σ_{eq} и ξ_{eq}, the concepts of the porosity v change rate of the material $\theta = dv/dt$ and the components of the strain rate tensor ξ_{ij}, are also used whose formulae as follows:

$$\theta = 9v(1-v)\sigma_0\xi_{eq} / \sigma_{eq}, \qquad (1)$$

$$\xi_{ij} = 3\xi_{eq}[\sigma_{ij} - (1-2v)\delta_{ij}\sigma_0] / 2\sigma_{eq}, \qquad (2)$$

where $\sigma_0 = \delta_{ij}\sigma_{ij}/3 = (\sigma_1+\sigma_2+\sigma_3)/3$ - is the mean normal stress, $\sigma_1, \sigma_2, \sigma_3$ – the principal normal stresses, σ_{ij} – the components of the stress tensor and δ_{ij} – the Kronecker symbol.

By the analytical method for the exact solutions of the hot drawing and extrusion problems of thin-walled porous tubes in a conical matrix is introduced in [4,5]. At this, taking into account the porosity material, systems of seven rather complex equations are obtained and solved whose application is difficult to realize in practice. That is why, a simplified solution to these problems is very important.

The goal of the work is to simplify the formula for determining the rate of change of porosity and its application for determining the porosity in different cross-sections of conical parts of the sintered thin-walled pipes at hot drawing and extrusion by using the known numerical component data on the stress state for the corresponding task of nonporous pipes.

1. Simplifying the formula for determining the porosity change rate of TS-TCHPM. In the technological processes of drawing and extrusion (Fig. 1) of thin-walled pipes, the main forming deformation is the circumferential, and hence the rate of circumferential deformation ξ_θ. Using equation (2) for the rate of circumferential deformation, we will obtain the following formula:

$$\xi_\theta = 3\xi_{eq}[\sigma_\theta - (1-2\nu)\sigma_0]/2\sigma_{eq}, \tag{3}$$

where σ_θ -is the circumferential stress.

From formula (3) we determine:

$$\xi_{eq} = \frac{2\,\xi_\theta \sigma_{eq}}{3[\sigma_\theta - (1-2\nu)\sigma_0]},$$

allowing to introduce formula (1) in the following simple form:

$$\theta = \frac{6\,\nu\,(1-\nu)\,\xi_\theta}{(\sigma_\theta/\sigma_0) - 1 + 2\nu}. \tag{4}$$

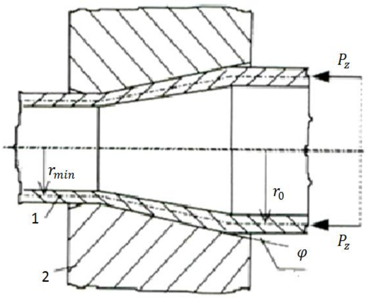

Fig. 1. **Scheme of the tube extrusion in a conical matrix and pressing**

Taking into account [1] that for a thin-walled tube, the increment of deformation in the circumferential direction $d\varepsilon_\theta$ is related to its radius r and its increment dr by the formula $d\varepsilon_\theta = dr/r$, as well as at hot deformation - the expressions $\theta = d\nu/dt$ and $\xi_\theta = d\,\varepsilon_\theta/dt$ or $\xi_\theta\;dt = d\,\varepsilon_\theta = dr/r$, formula (4) in dimensionless variables $r/r_0 = \bar{r}$, $dr/r_0 = d\bar{r}$ can be presented in the form:

$$d\nu = \frac{6\,\nu\,(1-\nu)}{(\bar{\sigma}_\theta/\bar{\sigma}_0) - 1 + 2\nu}\left(\frac{d\,\bar{r}}{\bar{r}}\right). \tag{5}$$

For carrying out numerical calculations formula (5) is given the form:

$$d\nu = A\left(\frac{d\,\bar{r}}{\bar{r}}\right), \tag{6}$$

where

$$A = \frac{6\,\nu\,(1-\nu)}{(\bar{\sigma}_\theta/\bar{\sigma}_0) - 1 + 2\nu}. \tag{7}$$

In order to obtain numerical data on the pipe drawing and extrusion in conical matrices, let us divide its deformation zone into small deformation degrees ($\Delta\bar{r}_i = -0{,}05$).Dimensionless numerical data on equivalent, meridional, circumferential and mean stresses ($\bar{\sigma}_{eq} = \sigma_{\mathrm{eq}}/\sigma_*$, $\bar{\sigma}_m = \sigma_{\mathrm{m}}/\sigma_*$, $\bar{\sigma}_\theta = \sigma_\theta/\sigma_*$, $\bar{\sigma}_0 = \sigma_0/\sigma_*$, where σ_* - is the mechanical characteristics of hot deformation of the material) [4] are used.

The porosity increment in the given degree of deformation is determined by the formula:

$$\Delta v = A(\frac{\Delta \bar{r}}{\bar{r}}), \qquad (8)$$

where the value of A is assumed constant and equal to the initial value in the given degree of deformation.

As for the determination of the current (after each degree of deformation) values of the pipe material porosity, the following formula is used:

$$v_i = v_{i-1} + \Delta v_i. \qquad (9)$$

It should be mentioned that to determine the current porosity of the material by using the differential equation (6) and the assumption of parameter A, a new formula can be obtained. For this, we should integrate (6) with the use of the following boundary condition for each degree of deformation: at $\bar{r} = \bar{r}_i$, $v = v_i$, i.e. the value of A after each degree of deformation changes. Then for the current porosity of the material, the following formula is obtained:

$$v_i = v_{i-1} - A_{i-1} \ln(\overline{r_{i-1}} / \overline{r_i}). \qquad (10)$$

2. Determining the porosity in different cross sections of the conical parts of sintered thin-walled pipes at hot drawing and extrusion. Table 1 shows the numerical data on the components of the stress state of the nonporous pipe hot-drawn task [4] at $\bar{\sigma}_{m0} = 0$, $\varphi = 14^\circ$, $f = 0{,}1$ and $\Delta\bar{r}_i = -0{,}05$, on whose basis porosity the increments at *ν₀ = 0, 2* were determined using formula (8), and the current porosity of the tube material by (9).

To obtain numerical data on the values of the current porosity of the extruded tube material at 20% of the initial porosity (Table 2) numerical data on the components of the stress state of the extrusion problem of a nonporous tube are also used. In this case, $\bar{\sigma}_{m0} = -0{,}072$, $\varphi = 14^\circ$, $f = 0{,}1$ and $\Delta\bar{r}_i = -0{,}05$.

Table 1. **Data on the solution of the tube hot-drawning tasks, at**
$v_0 = 0{,}2$, $\bar{\sigma}_{m0} = 0$, $\varphi = 14^\circ$, $f = 0{,}1$ *and* $\Delta\bar{r}_i = -0.05$

$\bar{r}$	$\bar{\sigma}_m$	$-\bar{\sigma}_\theta$	$-\bar{\sigma}_0$	$\frac{\bar{\sigma}_\theta}{\bar{\sigma}_0}$	$-\Delta\bar{r}/\bar{r}$	$-\Delta$ v	v
1	0	0.93	0.310	3	-	-	0.200
0.95	0.08	0.91	0.277	3.29	0.0500	0.0200	0.180
0.90	0.15	0.88	0.243	3.62	0.0526	0.0188	0.161
0.85	0.23	0.85	0.207	4.11	0.0556	0.0177	0.144
0.80	0.31	0.81	0.167	4.85	0.0588	0.0162	0.128
0.75	0.40	0.76	0.120	6.33	0.0625	0.0143	0.114

Table 2. **Data on the solution of the pipe hot extrusion problem**
when $v_0 = 0{,}2$, $\bar{\sigma}_{m0} = -0{,}072$, $\varphi = 14^\circ$, $f = 0{,}1$ *and* $\Delta\bar{r}_i = -0.05$

$\bar{r}$	$-\bar{\sigma}_m$	$-\bar{\sigma}_\theta$	$-\bar{\sigma}_0$	$\frac{\bar{\sigma}_\theta}{\bar{\sigma}_0}$	$\Delta\bar{r}$/r	$-\Delta v$	v	v [5]
1	0.07	1.030	0.370	2.80	-	-	0.20	0.2
0.95	0.06	1.029	0.360	2.83	0.050	0.021	0.18	0.17
0.9	0.05	1.035	0.361	2.86	0.052	0.023	0.16	0.15
0.85	0.04	1.040	0.363	2.89	0.055	0.024	0.13	0.13
0.8	0.02	1.050	0.356	2.93	0.059	0.025	0.11	0.11
0.75	0.01	1.052	0.353	2.98	0.063	0.026	0.08	0.09

Fig. 2 shows the graphs of the current porosity changes v by height of the conical part of the tubes, calculated by the formulae (8) and (9) at $v_0 = 0{,}2$: Curve 1 corresponds to the tube drawing, 2 – the extrusion, and the data of the points on the dashed curve are obtained by the exact solution of problem [5].

These solution of the problem show that:

- A simplified formula for determining the porosity in the conical parts of the sintered thin-walled pipes at hot drawing and extrusion is obtained,
- Two numerical calculation methods are propose for using the simplified formulae,
- Both at drawing and at extrusion of the porosity decreases pipe, which is explained by the negative mean stresses. At this, in case of extrusion, their absolute magnitudes are greater than at drawing, so at extrusion, the intensity of the material hardening is higher than it is at drawing.

Thus, the formula for determining the rate of change of porosity of TS-TCHPM is simplified. Using the data by the analytical methods of research of the stress-strain state at hot drawing and extrusion of thin-walled nonporous tubes in a conical matrix, porosities in different cross-sections of the conical parts of the sintered tubes are determined and the results are compared with both each other and the data of the exact solution of the corresponding tasks.

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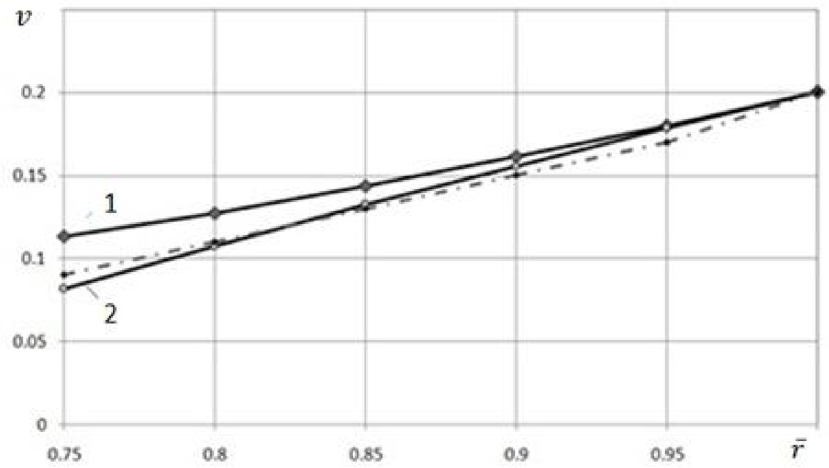

Fig. 2. **Graphs of changes of the current porosity v by height of the conical tubes at drawing curve 1 and 2- extrusion, the data points of the dashed curve correspond to [5]**

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