ISSN 0002-306X. Proc. of the RA NAS and NPUA Ser. of tech. sc. 2022. V. LXXV, N2

UDC 621.762, 620.10 **MECHANICAL ENGINEERING**

DOI: 10.53297/0002306X-2022.v75.2-169

A.A. BABAYAN

STUDYING THE EXTRUSION PROCESS OF A SINTERED THIN-WALL PIPE LOADED WITH INTERNAL HIGH PRESSURE IN CASE OF A BOUNDARY CONDITION IN THE DIE INLET

An analytical study of the process of sintered thin-wall pipe extrusion loaded with internal high pressure, on its cross section in the conical die inlet by compressing meridional dimensionless stress has been carried out. It is assumed that the external die pressure p_v and the internal high pressure p_r acting on the pipe are equal. In this case, the circumferential stress is determined and a simplified plasticity condition is obtained. The dimensionless values of meridional, circumferential and average stresses depending on the degree of pipe deformation were determined, which made it possible to study the processes of their compaction using the DTPPM equations at different values of coefficients of friction and initial porosities of the pipe material.

A computer simulation of the process was carried out in the MS EXEL software environment, presetting different initial values of the compressive meridional dimensionless stress. The pipe extrusion process will correspond to such an initial value of this stress, when the meridional stress of the pipe in the outlet of the die is equal to zero. In this case, the value of strain intensities is $\varepsilon_i = 0.258$.

The graphs of changes in 10, 20 and 30% of the initial porosities of the material show that the porosity becomes zero in the interval of value of deformation intensities ε_i from 0.116 to 0.132, and also in the case of large values of porosities and contact friction, the compaction of the material occurs more intensively.

***Keywords*:** thin-walled pipe, extrusion, boundary condition, circumferential stress, sintered material, computer simulation.

Introduction. Works [1, 2] are devoted to the study of the forming processes of thin-walled pipes made of rigid-strengthening solid materials using the Huber-Mises plasticity condition in the presence of contact friction. Moreover, in [2], the problem of the stress-strain state (SSS) at the extrusion of a non-porous pipe is solved in case of loading it with an internal pressure p_r, and the sintered pipe formation in conical dies is carried out in the absence of the internal pressure. In this case, based on the equations of the flow theory of porous materials (TFPM), the solutions of the problems of plastic deformation in a conical die of sintered monometallic thin-walled pipes of various porosities are given.

It should be noted that the solutions to these problems, which are of great practical importance, are quite complicated, since they are based on the integration of a system of four differential equations.

In [3], a computer simulation of extrusion processes in a conical die of bimetallic rods and pipes made of non-strengthened solid materials with different yield strengths of their inner layers (rod and pipe) has been carried out. Types of Mises stress zones and SSS components have been obtained for different large values of the numerical data of the yield strengths of the inner rod and pipe, which differ from each other.

The analysis of the radial σ_r and the circumferential $\sigma_\theta$stresses arising due to internal pressure on the outer pipe for bimetallic rods show that in the case of large yield strengths of the inner rod exceeding the yield strength of the outer pipe, the difference in the values of the outer pipe stresses (σ_r and σ_θ) is insignificant.

Based on the obtained stress zones σ_r and σ_θ, it is assumed that the pressures p_v and p_r, acting on the outer pipe are equal, i.e. $p_v \cong p_{r1}$,where p_v is the die pressure on the pipe in the normal direction. In this case, the circumferential tension of the outer pipe $\sigma_\theta = -p_v = -p_r$ is determined, as a result of which a simplified plasticity condition is obtained, and then the SSS of the outer pipe is investigated by the analytical method.

Taking into account the influence of high internal pressure p_r, in the presence of contact friction [3], when tangential stresses $p_m = f p_{v,}$ are formed on the pipe surface in the meridional direction, equilibrium equations [2] are given for solving the problems of plastic deformation of the pipe at a constant thickness of its wall ($h = const$), where f is the coefficient of friction. In this case, the plasticity condition is expressed through the absolute values of the stressed state components and is simplified by the analytical method of solving problems. The only resulting differential equation is solved using the boundary condition in the outlet of the conical die (the absence of meridional stresses). However, it is impossible to solve the problems of pressing bimetallic pipes in a conical die by this method. Consequently, works in this direction are topical.

The purpose of this work **is** to solve the problem of pressing a thin-wall pipe loaded with internal high pressure using the boundary condition in the inlet of a conical die by the analytical method.

Solutions to the problem of extrusion of thin-walled pipes loaded with internal high pressure. For this purpose, the equilibrium equations are used and, for plastic materials, the Huber-Mises plasticity condition, which is more precise, but rather complex one, takes into account the volumetric stress state [1, 2]:

Due to the complexity of the problem, as in [1,2], we will assume that the pressures p_v and p_r acting on the pipe are equal, that is, $p_v = p_r$. In this case, for the circumferential stress σ_θ we obtain:

$$\sigma_\theta = -p_v = -p_r. \quad (1)$$

When extruding the pipes loaded with internal high pressure, the main stresses σ_1, σ_2 and σ_3 will be as follows:

$$\sigma_1 = \sigma_m < 0,\ \sigma_2 = \sigma_3 = \sigma_\theta = -p_v = -p_r < 0, \quad (2)$$

consider that the Huber-Mises plasticity condition (PC) will look as follows:

$$\sigma_m - \sigma_\theta = \sigma_\text{T}, \quad (3)$$

where σ_m is the meridional stress and σ_T - the yield point.

Solving the basic equilibrium equation [2]

$$\frac{d}{dr}(\sigma_m r) - \sigma_\theta + \frac{2p_m}{sin2\,\alpha} = 0$$

with plasticity condition (3), we obtain formulas for determining the SSS components of thin-wall pipes during extrusion in a conical die. In the presence of friction ($f \neq 0$), i.e. $p_m = fp_v$, equations of equilibrium and PC for solving the problem in dimensionless stresses $\bar{\sigma}_m$ and $\bar{\sigma}_\theta$ will have the following form:

$$r\frac{d\bar{\sigma}_m}{dr} + \bar{\sigma}_m - \bar{\sigma}_\theta(1+k) = 0, \quad (4)$$

$$\bar{\sigma}_\theta = \bar{\sigma}_m - 1, \quad (5)$$

where $k = 2f/sin2\varphi$,

$$\bar{\sigma}_m = \sigma_m/\sigma_\text{T} \text{ and } \bar{\sigma}_\theta = \sigma_\theta/\sigma_\text{T}. \quad (6)$$

It should be noted that having the values of dimensionless stresses and yield strengths of materials from (6), we can determine the following formulas for true stresses σ_m and σ_θ, which are of great practical importance:

$$\sigma_m = \bar{\sigma}_m\sigma_\text{T},\ \sigma_\theta = \bar{\sigma}_\theta\sigma_\text{T}. \quad (7)$$

From the PC (5), substituting the value $\bar{\sigma}_\theta$ into the equilibrium equation (4) [2], and transforming it stepwise, we establish:

$$r\frac{d\bar{\sigma}_m}{dr} + \bar{\sigma}_m - (1+k)(\bar{\sigma}_m - 1) = 0, d\bar{\sigma}_m = \frac{dr}{r}(\bar{\sigma}_m k - (1+k)),$$

$$\frac{d\bar{\sigma}_m}{\bar{\sigma}_m k-(1+k)} = -\frac{dr}{r}, \frac{d(\bar{\sigma}_m k-(1+k))}{\bar{\sigma}_m k-(1+k)} = k\frac{dr}{r}. \quad (8)$$

By integrating this differential equation, we obtain:

$$ln(\bar{\sigma}_m k - (1+k)) = k\ln r + \ln C. \quad (9)$$

To determine the integration constant C, we first transform (9) to the following form:

$$ln[\bar{\sigma}_m k-(1+k))]=\ln(r^k C), \quad (10)$$

and then the boundary condition is used.

The boundary condition for pipe extrusion according to the scheme in Fig. 1 when it enters the die has the following form:
when

$$r=r_0, \bar{\sigma}_m=\bar{\sigma}_{m0}, \quad (11)$$

which allows to determine C from (10):

$$C=\frac{[\bar{\sigma}_{m0}k-(1+k)]}{r_0^k},$$

and then, putting it into (9), transforming it stepwise, we obtain a formula for determining the meridional stress $\bar{\sigma}_m$:

$$ln[\bar{\sigma}_m k-(1+k)]=ln,$$

$$\{[\bar{\sigma}_{m0}k-(1+k)](r/r_0)^k\},$$

$$\bar{\sigma}_m k-(1+k)=[\bar{\sigma}_{m0}k-(1+k)](r/r_0)^k,$$

$$\bar{\sigma}_m k=(1+k)+[\bar{\sigma}_{m0}k-(1+k)](r/r_0)^k,$$

$$\bar{\sigma}_m=\frac{1+k}{k}+\left(\bar{\sigma}_{m0}-\frac{1+k}{k}\right)(r/r_0)^k. \quad (12)$$

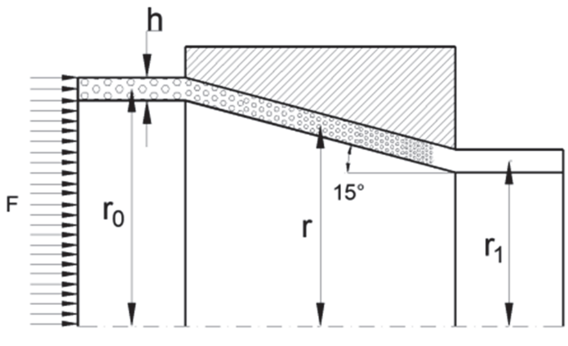

Fig. 1. The scheme of thin-walled pipe extrusion

For circumferential $\bar{\sigma}_{\theta 2}$ and for the compaction of sintered tube materials, which is of great importance, the average $\bar{\sigma}_0=(\bar{\sigma}_1+\bar{\sigma}_2+\bar{\sigma}_3)/3$ dimensionless stresses are determined by using formulas (1), (3) and (12):

$$\bar{\sigma}_\theta = -\bar{p}_v = \bar{\sigma}_m - 1 = -1 + \frac{1+k}{k} + \left(\bar{\sigma}_{m0} - \frac{1+k}{k}\right)(r/r_0)^k,$$

$$\bar{\sigma}_\theta = \frac{1}{k} + \left(\bar{\sigma}_{m0} - \frac{1+k}{k}\right)(r/r_0)^k, \tag{13}$$

$$\bar{\sigma}_0 = \frac{\bar{\sigma}_m + 2\bar{\sigma}_\theta}{3} = \frac{3+k}{3k} + \left(\bar{\sigma}_{m0} - \frac{1+k}{k}\right)(r/r_0)^k. \tag{14}$$

It should be noted that this problem is solved quite simply by the second boundary condition for pipe extrusion, which is made for its outlet part from the die (Fig. 1) and it has the following form:
when

$$r = r_1, \bar{\sigma}_{m1} = 0. \tag{15}$$

Here we give only the formulas for the following dimensionless components of the stress state ($\bar{\sigma}_{m*}, \bar{\sigma}_{\theta*}$) and the average stress $\bar{\sigma}_{0*}$ obtained using the boundary condition (15), which allow to compare them with formulas (12)-(14), and then with their numerical results:

$$\bar{\sigma}_{m*} = \frac{1+k}{k}\left(1 - \left(\frac{r}{r_1}\right)^k\right), \tag{16}$$

$$\bar{\sigma}_{\theta*} = \bar{\sigma}_{m*} - 1173 = \frac{1+k}{k}\left(1 - \left(\frac{r}{r_1}\right)^k\right) - 1 = \frac{1}{k} - \frac{1+k}{k}\left(\frac{r}{r_1}\right)^k, \tag{17}$$

$$\bar{\sigma}_{0*} = \frac{\bar{\sigma}_{m*} + 2\bar{\sigma}_{\theta*}}{3} = \frac{1}{3}\left(\frac{1+k}{k}\left(1 - \left(\frac{r}{r_1}\right)^k\right) + 2\left(\frac{1}{k} - \frac{1+k}{k}\left(\frac{r}{r_1}\right)^k\right)\right),$$

where

$$\bar{\sigma}_{0*} = \frac{1}{3}\left(\frac{3+k}{k} - \frac{3+3k}{k}\left(\frac{r}{r_1}\right)^k\right). \tag{18}$$

A comparison of formulas (12)-(14) and (16)-(18) shows that the main difference between them is the denominator of fractions of variable r of the problem: $\frac{r}{r_0}$ and $\frac{r}{r_1}$.

It should be noted that for determining the change in material porosity during the sintered pipe extrusion, the engineering analytical conjugate method is used in [3, 4], according to which the data obtained above and the equations of the deformation theory of plasticity of porous materials (DTPPM) [2] are used.

In [4], the yield stress of various sintered materials $\sigma_{\mathrm{T}v}$ is expressed through the yield strength of the porous material substance σ_{T} and the porosity function $\beta^{n+0,5}$:

$$\sigma_{Tv} = \sigma_T \cdot \beta^{n+0,5}, \qquad (19)$$

where v is the material porosity, $\beta = 1 - v$.

Consequently, to determine the true stresses σ_m and σ_θ , together with formulas (7), the following formulas should be used:

$$\sigma_m = \bar{\sigma}_m \beta^{n+0,5} \sigma_T, \sigma_\theta = \bar{\sigma}_\theta \beta^{n+0,5} \sigma_T. \qquad (20)$$

It is necessary to use the following formula DTPPM [2] for the determination of the values of the current porosity of material v:

$$v = 1 - (1 - v_0) \exp\left(-\frac{9 v_0^m \sigma_0 \varepsilon_{eq0}}{(1-v_0)^{3n} \sigma_{eq0}}\right), \qquad (21)$$

where v_0 is the initial porosity of the material; $\sigma_{eq0} = \sigma_T$ and $\varepsilon_{eq0} = \bar{\varepsilon}_i = 1{,}155|\bar{\varepsilon}_\theta|$- the respectively simplified values of equivalent stresses and deformations [1,2]; r_0 - the initial radius of the pipe (Fig.1); m and n are the porosity parameters.

The results of the research. To solve the problem of thin-wall pipe extrusion, the following parameters were given: cone angle of matrix - $\varphi = 15°$, the outer diameters of the pipe blank and the product - $D = 25$ *mm* and $d = 20$ *mm*, the pipe thickness – 2 *mm*, the yield strength - $\sigma_T = 350$ *MPa.*

Taking into account $k = 2f / \sin 2\varphi$, numerical calculations of the pipe extrusion process loaded with internal pressure were performed in the MS EXEL software environment for various friction coefficients ($f = 0{,}05;\ 0{,}1$ и $0{,}15$). In these cases, the values of the coefficient k will be 0,2; 0,4 and 0,6.

Tables 1-4 and Fig. 2 show the data of SSS at $k = 0{,}4$ and 0,6; initial material porosities $v_0 = 0{,}1;\ 0{,}2$ and 0,3 in the case of $m = 1$ and $n = 0{,}25$ [2].

Numerical calculations were performed by formulas (12)-(14) in the absence of initial values of compressible meridional dimensionless stress $\bar{\sigma}_{m20}$, therefore a computer simulation of the process was performed in the MS EXEL software environment by pre-setting different initial values $\bar{\sigma}_{m0}$. The pipe extrusion process will corresponded to a value $\bar{\sigma}_{m0}$ when the pipe meridional stress $\bar{\sigma}_m$ equals 0 in the outlet of die.

In Tables 1-3, at $k = 0{,}4$, the data of SSS given are for three values $\bar{\sigma}_{m0}$ $(-0{,}326;\ -0{,}327$ и $-0{,}328)$, from which it follows that in the average case $\bar{\sigma}_{m0} = -0{,}327$, the meridional stress has acquired the value 0 in the die outlet. At $k = 0{,}6$, in the die inlet, the case $\bar{\sigma}_{m0} = -0{,}382$ was also found by computer simulation (Table 4), when the meridional stress $\bar{\sigma}_m = 0$ in the die outlet.

Table 1

Numerical calculation data in the presence of friction ($k = 0{,}4$) and initial meridional stress $\bar{\sigma}_{m0} = -0{,}326$

r/r_0	$-\bar{\varepsilon}_\theta$	$\bar{\varepsilon}_i$	$-\bar{\sigma}_m$	$-\bar{\sigma}_\theta$	$-\bar{\sigma}_0$	ν_1	ν_2	ν_3
1	0	0.000	0.326	1.326	0.993	0.100	0.200	0.300
0.98	0.020	0.023	0.295	1.295	0.962	0.080	0.161	0.242
0.96	0.041	0.047	0.264	1.264	0.931	0.061	0.122	0.183
0.94	0.062	0.071	0.232	1.232	0.899	0.042	0.083	0.122
0.92	0.083	0.096	0.200	1.200	0.867	0.024	0.044	0.060
0.9	0.105	0.122	0.168	1.168	0.835	0.006	0.007	-0.002
0.88	0.128	0.148	0.135	1.135	0.802	-0.010	-0.029	-0.063
0.86	0.151	0.174	0.102	1.102	0.769	-0.025	-0.064	-0.123
0.84	0.174	0.201	0.068	1.068	0.735	-0.040	-0.096	-0.180
0.82	0.198	0.229	0.034	1.034	0.701	-0.052	-0.126	-0.234
0.8	0.223	0.258	-0.001	0.999	0.666	-0.064	-0.153	-0.283

Table 2

Numerical calculation data in the presence of friction ($k = 0{,}4$) and initial compressive meridional stress $\bar{\sigma}_{m0} = -0{,}327$

r/r_0	$-\bar{\varepsilon}_\theta$	$\bar{\varepsilon}_i$	$-\bar{\sigma}_m$	$-\bar{\sigma}_\theta$	$-\bar{\sigma}_0$	ν_1	ν_2	ν_3
1	0	0.000	0.327	1.327	0.994	0.100	0.200	0.300
0.98	0.020	0.023	0.296	1.296	0.963	0.080	0.161	0.242
0.96	0.041	0.047	0.265	1.265	0.932	0.061	0.122	0.183
0.94	0.062	0.071	0.233	1.233	0.900	0.042	0.083	0.122
0.92	0.083	0.096	0.201	1.201	0.868	0.024	0.044	0.060
0.9	0.105	0.122	0.169	1.169	0.836	0.006	0.007	-0.002
0.88	0.128	0.148	0.136	1.136	0.803	-0.010	-0.030	-0.064
0.86	0.151	0.174	0.103	1.103	0.770	-0.026	-0.064	-0.123
0.84	0.174	0.201	0.069	1.069	0.736	-0.040	-0.097	-0.181
0.82	0.198	0.229	0.035	1.035	0.702	-0.053	-0.126	-0.235
0.8	0.223	**0.258**	0.000	1.000	0.667	-0.064	-0.153	-0.284

Table 3

Numerical calculation data in the presence of friction ($k = 0{,}4$) and initial compressive meridional stress $\bar{\sigma}_{m0} = -0{,}328$

r/r_0	$-\bar{\varepsilon}_\theta$	$\bar{\varepsilon}_i$	$-\bar{\sigma}_m$	$-\bar{\sigma}_\theta$	$-\bar{\sigma}_0$	ν_1	ν_2	ν_3
1	0	0.000	0.328	1.328	0.995	0.100	0.200	0.300
0.98	0.020	0.023	0.297	1.297	0.964	0.080	0.161	0.242
0.96	0.041	0.047	0.266	1.266	0.933	0.061	0.122	0.183
0.94	0.062	0.071	0.234	1.234	0.901	0.042	0.083	0.121
0.92	0.083	0.096	0.202	1.202	0.869	0.024	0.044	0.060
0.9	0.105	0.122	0.170	1.170	0.837	0.006	0.006	-0.003
0.88	0.128	0.148	0.137	1.137	0.804	-0.010	-0.030	-0.064
0.86	0.151	0.174	0.104	1.104	0.771	-0.026	-0.064	-0.124
0.84	0.174	0.201	0.070	1.070	0.737	-0.040	-0.097	-0.182
0.82	0.198	0.229	0.036	1.036	0.703	-0.053	-0.127	-0.235
0.8	0.223	0.258	0.001	1.001	0.668	-0.064	-0.154	-0.285

Table 4

Numerical calculation data in the presence of friction ($k = 0{,}6$) and initial compressive meridional stress $\bar{\sigma}_{m0} = -0{,}382$

r/r_0	$-\bar{\varepsilon}_\theta$	$\bar{\varepsilon}_i$	$-\bar{\sigma}_m$	$-\bar{\sigma}_\theta$	$-\bar{\sigma}_0$	ν_1	ν_2	ν_3
1	0	0.000	0.382	1.382	1.049	0.100	0.200	0.300
0.98	0.020	0.023	0.345	1.345	1.012	0.079	0.159	0.239
0.96	0.041	0.047	0.308	1.308	0.975	0.059	0.118	0.177
0.94	0.062	0.071	0.271	1.271	0.938	0.039	0.077	0.113
0.92	0.083	0.096	0.233	1.233	0.900	0.021	0.038	0.050
0.9	0.105	0.122	0.195	1.195	0.862	0.003	0.000	-0.013
0.88	0.128	0.148	0.157	1.157	0.824	-0.013	-0.036	-0.075
0.86	0.151	0.174	0.118	1.118	0.785	-0.028	-0.070	-0.134
0.84	0.174	0.201	0.079	1.079	0.746	-0.042	-0.101	-0.189
0.82	0.198	0.229	0.040	1.040	0.706	-0.054	-0.129	-0.239
0.8	0.223	**0.258**	**0.000**	1.000	-0.667	-0.064	-0.153	-0.283

Numerical calculations in case of the second boundary condition are carried out by formulas (16)-(18), which do not differ much from the data of formulas (12)-(14). Therefore, in this case, there is no need to show the full tabular data of the SSS research and only short data are given in Tables 5 and 6.

Table 5

Numerical calculation data in the presence of friction ($k = 0{,}4$) and boundary pipe extrusion condition, for its die outlet: $r = r_1, \bar{\sigma}_{m1} = 0$

$\bar{\varepsilon}_\theta$	$\bar{\varepsilon}_i$	r/r_1	$\bar{\sigma}_m$	$\bar{\sigma}_\theta$	$\bar{\sigma}_0$	ν_1	ν_2	ν_3
0	0	1.250	-0.327	-1.327	-0.993	0.100	0.200	0.300
-0.020	0.023	1.225	-0.296	-1.296	-0.963	0.080	0.161	0.242
-0.041	0.047	1.200	-0.265	-1.265	-0.931	0.061	0.122	0.183

Table 6

Numerical calculation data in the presence of friction ($k = 0{,}6$) and boundary pipe extrusion condition, for its die outlet: $r = r_1,\ \bar{\sigma}_{m1} = 0$

$\bar{\varepsilon}_\theta$	$\bar{\varepsilon}_i$	r/r_1	$\bar{\sigma}_m$	$\bar{\sigma}_\theta$	$\bar{\sigma}_0$	ν_1	ν_2	ν_3
0	0	1.250	-0.382	-1.382	-1.049	0.100	0.200	0.300
-0.020	0.023	1.225	-0.345	-1.345	-1.012	0.079	0.159	0.239
-0.041	0.047	1.200	-0.308	-1.308	-0.975	0.059	0.118	0.177

A comparison of the numerical data calculated by formulas (12)-(14) and (16)-(18) shows that the main difference between them is the column r of the task variable problem $\frac{r}{r_0}$ and $\frac{r}{r_1}$, which provides an exact match of the main results.

The graphs of changes in the dimensionless values of meridional, circumferential and average stresses, as well as material porosity, depending on the degree of pipe deformation are shown in Figures 2 and 3.

It can be seen from Fig. 3 that 10, 20 and 30% of the initial porosity of the material becomes zero in the range of strain intensities $\bar{\varepsilon}_i$ from 0.116 to 0.132, and in case of larger porosities and contact friction, the compaction of the material is more intense.

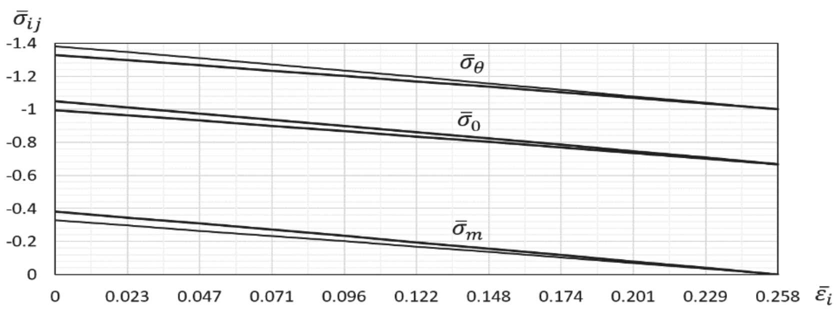

Fig. 2. Graphs of change in dimensionless values of meridional, circumferential and medium stresses

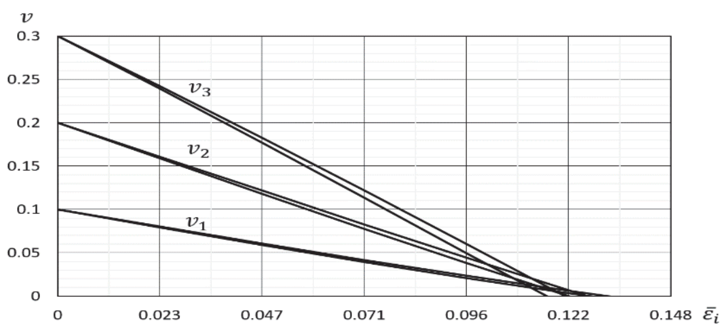

Fig. 3. Graphs of changes in 10, 20 and 30% of the initial porosity of materials

Conclusions

1. A study of the process of extrusion of thin-wall pipe loaded with internal high pressure with boundary condition in the inlet of a conical die, when the initial values of compressible meridional dimensionless stress $\bar{\sigma}_{m20}$ are absent, has been carried out. The dimensionless values of meridional, circumferential and average stresses depending on the degree of pipe deformation were determined, which allowed to study the process of pipe material compaction using the DTPPM equations at various values of friction coefficients.

2. A computer simulation of the process was carried out in the MS EXEL software environment, presetting different initial values $\bar{\sigma}_{m0}$. The pipe extrusion process will correspond to the value $\bar{\sigma}_{m0}$, when the pipe meridional stress $\bar{\sigma}_{m}$ equals 0 in the outlet of the die. In this case, the strain intensity value is $\varepsilon_i = 0{,}258$.

3. The data of numerical calculations show that at the coefficient of friction $f = 0{,}1$ $(k = 0{,}4)$, it has been established, with computer simulation, that in case of a dimensionless compressive, the initial value of the meridional stress is $\bar{\sigma}_{\mathrm{m0}} = -0{,}327$, in the die outlet, the meridional stress acquired the value 0. And in the case of coefficient of friction $f = 0{,}15\,(k = 0{,}6)$, the meridional stress at $\bar{\sigma}_{m0} = -0{,}382$ acquired the value 0 in the die outlet.

4. The graphs of changes in 10, 20 and 30% of the initial porosities of the material show that the porosity becomes zero in the range of strain intensities ε_i from 0,116 to 0,132, and in the case of large values of porosities and contact friction, the material compaction is more intense.

5. In order to verify the obtained formulas and the results of numerical calculations, the problem is solved quite simply by the second boundary condition for the pipe extrusion, composed for the outlet part of the pipe from the die $(r = r_1)$, where the meridional stress is absent $(\bar{\sigma}_{m1} = 0)$. It has been found that both solutions are identical.

REFERENCES

1. **Malinin N.N.** Applied theory of plasticity and creep. - M.: Mechanical engineering, 1975. - 399 p.
2. **Petrosyan G.L.** Plastic deformation of powder materials. - M.: Metallurgy, 1988. – 153 p.
3. **Petrosyan G.L., Babayan A.A., Margaryan M.A.** Computer simulation and analytical research of the extrusion process of a thin-walled pipe loaded by internal high pressur // Bulletin of the National Polytechnic University of Armenia (NPUA): Mech., Mach. Sci., Mach. Build. - 2020. - No. 2. – P. 9-22.
4. **Petrosyan G.L., Margaryan M.A., Vardanyan G.G., Babayan A.A.** Investigating the process of drawing of a thin-walled sintered pipe through a conical matrix // Proceedings NAS of Armenia and NPUA. Series of Technical Sciences. - 2019.- Vol. 72, No. 1. - P. 5-14.

National Polytechnic University of Armenia. The material is received on 01.07.2022.

Ա.Ա. ԲԱԲԱՅԱՆ

ՆԵՐՔԻՆ ԲԱՐՁՐ ՃՆՇՈՒՄՈՎ ԲԵՌՆԱՎՈՐՎԱԾ ԵՌԱԿԱԼՎԱԾ ԲԱՐԱԿԱՊԱՏ ԽՈՂՈՎԱԿԻ ԱՐՏԱՄՂՄԱՆ ԳՈՐԾԸՆԹԱՑԻ ՀԵՏԱԶՈՏՈՒՄԸ ՄԱՄԼԱՄԱՅՐ ՄՏՆՈՂ ԵԶՐԱՅԻՆ ՊԱՅՄԱՆԻ ԴԵՊՔՈՒՄ

Կատարվել է ներքին բարձր ճնշումով բեռնավորված եռակալված խողովակի կոնական մամլամայրում մամլման գործընթացի հետազոտում՝ վերլուծական մեթոդով, դրա մամլամայր մտնող վերին լայնական հատույթին սեղմող միջօրեական լարում կիրառելով: Ենթադրվում է, որ խողովակի վրա ազդող մամլամայրի հպակային p_v և դրա ներսում ազդող p_r ճնշումները հավասար են: Այդ դեպքում որոշվում է խողովակի շրջանային լարումը, և ստացվում է պարզեցված պլաստիկության պայման: Որոշվել են խողովակի դեֆորմացման աստիճանից կախված միջօրեական, շրջանային և միջին լարումների չափազուրկ մեծությունները, որոնք հնարավորություն են տվել, օգտագործելով ծակոտկեն նյութերի պլաստիկության դեֆորմացիոն տեսության բանաձևերը, տարբեր շփման գործակիցների և խողովակի նյութի սկզբնական ծակոտկենության դեպքերում ուսումնասիրել դրանց խտացման գործընթացը:

MS EXEL ծրագրային միջավայրում կատարվել է գործընթացի համակարգչային մոդելավորում տարբեր սկզբնական սեղմող միջօրեական չափազուրկ լարումների դեպքում: Խողովակի արտամղման գործընթացին կհամապատասխանի այդ լարման այնպիսի սկզբնական մեծություն, երբ խողովակի միջօրեական լարումը մամլամայրից դուրս գալու ժամանակ կհավասարվի զրոյի: Այդ դեպքում դեֆորմացիաների ինտենսիվության արժեքը հավասար է $\varepsilon_i = 0{,}258$:

10, 20 և 30% սկզբնական ծակոտկենությամբ նյութի կորերի փոփոխությունները ցույց են տալիս, որ ծակոտկենությունը դառնում է զրո դեֆորմացիաների ինտենսիվության ε_i 0,116 – ից մինչև 0,132 միջակայքում: Ծակոտկենության և հպակային շփման մեծ արժեքների դեպքում նյութի խտացումը տեղի է ունենում ավելի ինտենսիվ:

Առանցքային բառեր. բարակապատ խողովակ, արտամղում, եզրային պայման, շրջանային լարում, եռակալված նյութ, համակարգչային մոդելավորում:

А.А. БАБАЯН

ИССЛЕДОВАНИЕ ПРОЦЕССА ЭКСТРУЗИИ СПЕЧЕННОЙ ТОНКОСТЕННОЙ ТРУБЫ, НАГРУЖЕННОЙ ВНУТРЕННИМ ВЫСОКИМ ДАВЛЕНИЕМ, ПРИ ВХОДЕ В МАТРИЦУ В СЛУЧАЕ ГРАНИЧНОГО УСЛОВИЯ

Проведено аналитическое исследование процесса экструзии спеченной тонкостенной трубы, нагруженной внутренним высоким давлением, при входе в коническую матрицу с использованием сжимающего меридионального безразмерного напряжения на ее поперечном сечении. Предполагается, что действующие на трубу внешнее давление матрицы p_v и внутреннее высокое давление p_r равны. В этом случае определяется окружное напряжение и получается упрощенное условие пластичности. Определены безразмерные величины меридиональных, окружных и средних напряжений в зависимости от степени деформации трубы, которые позволили с использованием уравнений деформационной теории пластичности пористых материалов при различных значениях коэффициентов трения и начальных пористостей материала труб изучить процессы их уплотнения.

Проведено компьютерное моделирование процесса в программной среде MS EXEL при различных начальных значениях сжимающего меридионального безразмерного напряжения. Процессу экструзии трубы соответствует такое начальное значение этого напряжения, когда меридиональное напряжение трубы при выходе из матрицы равняется нулю. При этом величина интенсивностей деформации равна $\varepsilon_i = 0{,}258$.

Графики изменения начальных пористостей материала 10, 20 и 30% показывают, что пористость становится нулевой в интервале величины интенсивностей деформации ε_i от 0,116 до 0,132. В случае больших величин пористостей и контактного трения уплотнение материала происходит более интенсивно.

Ключевые слова: тонкостенная труба, экструзия, граничное условие, окружное напряжение, спеченный материал, компьютерное моделирование.