

Mathematical modelling of pressing process of bimetallic pipes



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Abstract

The hydrodynamic model of pressing process of bimetallic pipes is accepted and its basis is given. The task about bimetallic pipes pressing by using of mathematical modeling of processes dynamics and the movement of bimetal and metal layers in the annular space of deformation zone between a matrix and a mandrel is solved. The differential equations of the movement of two-layer flow of bimetal and metal in the deformation zone considering the rheology of the working environment are worked out. Power and dynamic parameters of the deformation zone when bimetallic pipes pressing considering a form of a working surface of the processing tool are determined. The formation features of bimetal and metal layers in the deformation zone are revealed.

Key words: PRESSING, MATRIX, MANDREL, DEFORMATION, BIMETALLIC PIPE, DYNAMICS, PRESSURE GRADIENT, VISCOSITY, RATE OF FLOW

Introduction. The priority in the field of weldless bimetallic pipes production from a combination of various materials (steels and special alloys) is determined by a number of advantages of technological and rational technical and economic indicators of modern pressing process [1, 2].

Along with others, the highly effective process of bimetallic pipes hot pressing found a wide application in the world practice. This process is often used by production of multilayered pipes from low-plastic materials and hard-to-deform alloys.

Problem statement. Increase of production efficiency of bimetallic pipes by improvement of pressing technology and pressure equipment puts forward a very promising task of making of the cardinal decisions associated with optimum control of products quality [3, 4].

Prediction of quality indicators of bimetallic pipes and bimetallic compounds and also increase of service durability of processing tools (matrixes and mandrels) and functioning reliability of the equipment take the leading place in these conditions.

Analysis of references. Within an objective, optimization of existing and development of new technological processes of bimetallic pipes production defi-

nitely indicates the correctness of mathematical models, and sometimes attraction of nonconventional rheology [5, 6]. The development of adequate model of modern technological process of bimetallic pipes pressing puts forward certain suppositions for rather full and all-round optimization of impact of various factors, parameters and modes of pressing at the corresponding stages of pipes pressing processes.

When bimetallic pipes pressing, the conditions of formation of the deformation zone power parameters cause the heavy loaded modes of loading and premature wear of processing tools (matrix, mandrel, container). When bimetallic pipes pressing, the special process lubrication is mainly used in order to reduce the friction forces in the deformation zone made from various steels components and their alloys [6, 7]. Therefore, high quality of a surface of the pressed bimetallic pipes from low-plastic materials and the required wear resistance of the processing tool is provided also with the use of various ways of feeding and variations of process lubrications. Special powders, lubricant washers, liquid or vitreous lubrication are usually used for this purpose in the industrial conditions (Fig. 1).

Furthermore, the problem of steady parameters

selection of pressing process that is intimately connected with the task solution of formation of a nec-

essary bimetallic layer between metal and processing tools (mandrel and matrix) is brought to the forefront.



Figure 1. Wear pattern of matrix a) and mandrel b) of pipe section press.

Possibilities of bimetallic pipes pressing with rather high deformation rates without violation of their required geometrical dimensions and without destruction of a bimetallic product continuity at an outlet from the deformation zone cause the

development of principally new rheology of the pressed materials, mathematical and nonconventional physical models of technological process (Fig. 2).



Figure 2. Templates of the pressed finished bimetallic pipes with a number of violations of a bimetallic layer.

Nevertheless, there is a number of difficulties of mathematical nature when developing and analysing of the specific objectives requiring the accounting of dynamic features of bimetallic pipes pressing real processes and physical and mechanical properties of bimetallic compounds materials on the basis of the fundamental plasticity theory.

Let us note that there is a number of researchers with somewhat different statement. For example, some specific tasks of the bimetallic pipes production technology are considered in papers [2, 4]. It should be noted that in the existing sources, there are no definite generalizing recommendations about definition of the pressing rational modes and selection of the deformation zone parameters. The accounting of dynamic features of a two-layer bimetallic flow of metal movement in the limited deformation zone volume and annular space between processing tools is very difficult.

Knowledge deepening of combined deformation processes of dissimilar metals and the nature of their combined functioning in the deformation zone is necessary. In this paper below, the attempt to achieve rather correct dynamic model of bimetallic pipes pressing process on the basis of fluid-flow analogy is made, and some calculations on the matter are given.

Thus, the bimetallic pipes pressing process is considered in the specified form that corresponds to the chosen viscoplastic rheology of model, physical and dynamic boundary conditions of the deformation zone within an objective.

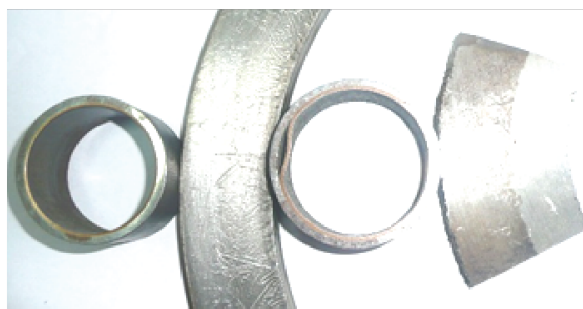
Work objective. The objective of this work is obtaining of recommendations about rational parameters selection of process and dynamic model for the most widespread patterns of bimetallic pipes pressing: "mandrel – bimetal – metal – matrix" and "mandrel – metal – bimetal – matrix".

Task solution. The physical representations, which are put in the basis of pressed materials rheology and the generalized hydrodynamic model, characterize the pressing modes and are adequate to the conditions of the constrained deformation zone. In particular, it takes place when producing of two-layer pipes from hardly deformed materials in combination with bimetals in the conditions of the selected design model (Fig. 3).

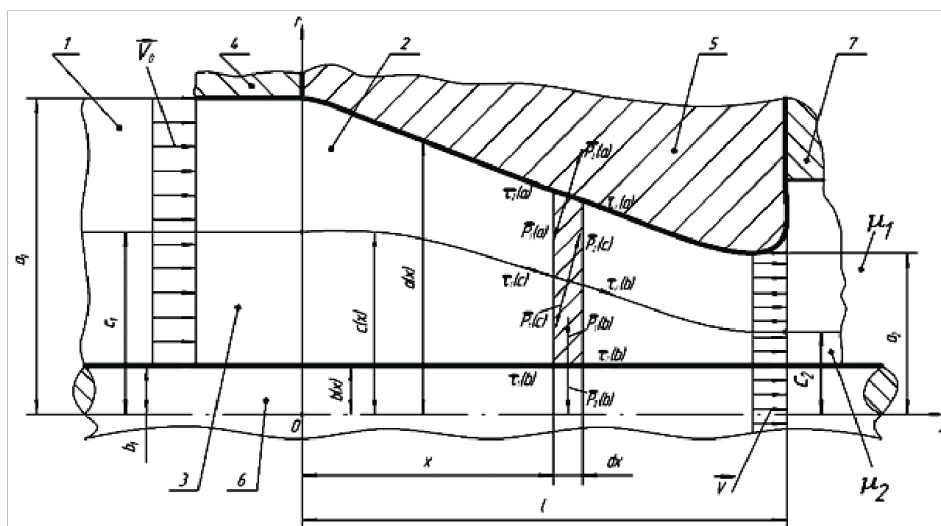
The pressing process of two-layer bimetallic pipes on a profile press is mainly carried out in the following order. Under the influence of the press-stamp 1 moving along a pressing axis with the specified speed V_0 of bimetal 2 "viscosity" μ_1 , and metal 3 of "viscosity" μ_2 are pressed from the container 4 in the annular space formed by a matrix 5 and a cylindrical mandrel 6; then, it is formed in a cylindrical bimetallic pipe (shell) with the specified geometrical dimensions.

Therefore, let us consider an axisymmetric two-layer bimetal and metal flow with the corresponding "viscosity" factor, in the annular space between matrix and mandrel within a nonconventional rheology, hydrodynamic model of the deformation zone and the accepted design model. The corresponding "viscosity" factors of bimetal and metal are defined by graphic differentiation of mechanical characteristics of layers materials [8].

For the dynamic processes research when bimetallic pipes pressing, within an objective, let us select the hydrodynamic two-layer model that allows further using of Navier-Stokes differential equations system with known assumptions and estimates according to [9, 11, 12].



a)



b)

Figure 3. Templates of bimetal billets a) and the design model of bimetal billets pressing process b) in the finished pipes: 1 – press-stamp; 2 – bimetallic layer; 3 – metal layer; 4 – container; 5 – matrix; 6 –mandrel; 7 – matrix-holder.

Let us note that if axisymmetric property of movement process of metal and bimetal layers (operating environments) is followed carefully in the deformation zone, we obtain the following system of the equations

$$\begin{cases} \frac{\partial p_1}{\partial x} = \mu_1 \left(\frac{\partial^2 v_{x1}}{\partial r^2} + \frac{1}{r} \frac{\partial v_{x1}}{\partial r} + \frac{\partial^2 v_{x1}}{\partial x^2} \right); \\ \frac{\partial p_2}{\partial x} = \mu_2 \left(\frac{\partial^2 v_{x2}}{\partial r^2} + \frac{1}{r} \frac{\partial v_{x2}}{\partial r} + \frac{\partial^2 v_{x2}}{\partial x^2} \right). \end{cases} \quad (1)$$

From the analysis of the differential equations system, it follows that pressure gradient in the considered section of the deformation zone is the function of selected variable of coordinate x . Thus, at that, the continuity equations should be worked out in the form of integrated expenses preservation laws according to bimetal and metal layers in the annular space of the deformation zone. Thus, according to the flow rate preservation law of bimetal and metal layers in the annular space between tools and the conditions of deformation zone continuity in the course of bimetallic two-layer pipes pressing, let us write down the following

$$\begin{cases} 2\pi \int_{b(x)}^{c(x)} v_{x1}(x,r) r dr = Q_1; \\ 2\pi \int_{c(x)}^{a(x)} v_{x2}(x,r) r dr = Q_2. \end{cases} \quad (2)$$

Let us suppose that smooth change of the cross section area of the deformation zone loaded with metal and bimetal. Let us consider the insignificant effect of rate change on the corresponding radial coordinate despite the strictness of dependence $v_{\delta 1,2}$ on both coordinate x and the radial sizes of the deformation zone. Obviously, in this case, let us transform system of the differential equations (1) neglecting a derivative $\frac{\partial^2 v_{x1,2}}{\partial \delta^2}$ in comparison with another additive component of the right part. Whence, it follows that the considered dynamic model of process for a characteristic two-layer flow of operating environments in the annular space of deformation zone section may be presented as quasi-stationary flow.

Within the hydrodynamic analogy task, for the process of bimetallic pipes pressing, we have the adapted system of the differential equations in the form of transformations

$$\begin{cases} \frac{\partial p_1}{\partial x} = \mu_1 \left(\frac{\partial^2 v_{x1}}{\partial r^2} + \frac{1}{r} \frac{\partial v_{x1}}{\partial r} \right); \\ \frac{\partial p_2}{\partial x} = \mu_2 \left(\frac{\partial^2 v_{x2}}{\partial r^2} + \frac{1}{r} \frac{\partial v_{x2}}{\partial r} \right). \end{cases} \quad (3)$$

On the basis of hydrodynamic analogy of process of metal and bimetal flow due to the above mentioned, the solution of the differential equations system (3) is presented according to [7, 8] in the form

$$\begin{cases} v_{x1}(\delta, r) = \frac{1}{4\mu_1} \left(\frac{\partial p_1}{\partial \delta} \right) r^2 + A_1 \ln r + B_1; \\ v_{x2}(\delta, r) = \frac{1}{4\mu_2} \left(\frac{\partial p_2}{\partial \delta} \right) r^2 + A_2 \ln r + B_2. \end{cases} \quad (4)$$

The equations (4) characterize the rates of the adjoint hydrodynamic flow of metal and bimetal layers in the deformation zone during pressing. The kinematic and boundary conditions for constants $A_{1,2}$ and $B_{1,2}$ determination are characteristic conditions of bimetal and metal sticking to processing tools. Thus, on a radius matrix $r = a(x)$ and internal mandrel of radius $r = b(x)$, the conditions of power parameters equality on the adjoint borders of layers contact will be presented in a form

$$v_{x1} = v_{x2} = u(x), \text{ when } r = c(x).$$

where $u(x)$ – the rate of the adjoint borders of bimetal and metal movement in the considered section x of the deformation zone, which radius is equal to $c(x)$.

It should be noted that both the rate of the borders movement $u(x)$ and border radius $c(x)$ are unknown in the considered deformation zone section within the adjoint zones when bimetallic pipe pressing. Then, from the system of the equations (4), considering the boundary conditions of the task for the adjoint zones of metal and bimetal, the layers movement rates in the deformation zone are defined

$$v_{x1}(\delta, r) = \frac{1}{4\mu_1} \frac{\partial p_1}{\partial x} (r^2 - b^2) + A_1 \ln \frac{r}{b}; \quad (5)$$

$$v_{x2}(\delta, r) = \frac{1}{4\mu_2} \frac{\partial p_2}{\partial x} (r^2 - a^2) + A_2 \ln \frac{r}{a}. \quad (6)$$

respectively.

Therefore, by simple transformations, from system of the equations (5) and (6), we find A_1 and A_2 respectively.

Considering the practical conditions of pressing process and features of a two-layer metal and bimetal

flow, on interface of the metal and bimetal adjacent zones of radius $c(x)$, we obtain

$$A_1 = \frac{u - \frac{1}{4\mu_1} \frac{\partial p_1}{\partial x} (c^2 - b^2)}{\ln \frac{c}{b}}; \quad A_2 = \frac{-u - \frac{1}{4\mu} \cdot \frac{\partial p_2}{\partial x} (a^2 - c^2)}{\ln \frac{a}{c}}; \quad B_1 = 0; \quad B_2 = 0. \quad (7)$$

We find the continuity condition of layers discharge through the cross sections of the deformation zone from a continuity condition of metal and bimetal

flow. Obviously, for metal and bimetal layers respectively on their interface, we obtain the following

$$Q_1 = 2\pi \int_b^c v_{x1} r dr = \frac{f_1}{\mu_1} \cdot \frac{\partial p_1}{\partial x} + g_1 u; \quad (8)$$

$$Q_2 = 2\pi \int_b^c v_{x2} r dr = \frac{f_2}{\mu_2} \cdot \frac{\partial p_2}{\partial x} + g_2 u, \quad (9)$$

where $f_1 = \frac{\pi}{8} (c^2 - b^2) \frac{c^2 - b^2 - (c^2 + b^2) \ln \frac{c}{b}}{\ln \frac{c}{b}}, \quad f_2 = \frac{\pi}{8} (a^2 - c^2) \frac{a^2 - c^2 - (a^2 + c^2) \ln \frac{a}{c}}{\ln \frac{a}{c}},$

$$g_1 = \frac{\pi}{\ln \frac{c}{b}} \left[c^2 \ln \frac{c}{b} - \frac{1}{2} (c^2 - b^2) \right], \quad g_2 = \frac{\pi}{\ln \frac{a}{c}} \left[\frac{1}{2} (a^2 - c^2) - c^2 \ln \frac{a}{c} \right].$$

If the movement rate of the press tool (press-stamp) V_O is specified, and bimetal thickness under a press-stamp $(a_1 - c_1)$ is known, at $x = 0$, the layers discharge value of bimetal and metal are known and equal to

$$Q_1 = \pi (c_1^2 - b_1^2) v_0, \quad Q_2 = \pi (a_1^2 - c_1^2) v_0. \quad (10)$$

Let us use the dynamic conditions of interaction on border of metal contact with a bimetal layer in the deformation center in order to determine the unknown kinematic $u(x)$ and geometrical $c(x)$ parameters of the deformation zone. We accept that the cor-

responding pressure and shear stress between metal and bimetal layers must be equal in the module and opposite in the direction on the interface of the adjacent zones of bimetallic connection at some requirements of specifications on absence of sliding (layering). According to the assumption that the inclination of the forming border of bimetal and metal contact to an axis of rolling is small ($c'(x) \ll 1$), the above condition is reduced to the following equalities

$$p_1 = p_2 \quad \text{when} \quad r(x) = c(x), \quad (11)$$

and

$$\tau_{xr}^1 = \mu_1 \frac{\partial v_{x1}}{\partial r} \Big|_{r=c(x)}, \quad \tau_{xr}^2 = \mu_2 \frac{\partial v_{x2}}{\partial r} \Big|_{r=c(x)} \quad \text{when} \quad r(x) = c(x). \quad (12)$$

It follows that pressure is identical throughout the cross section of the two-layer environment $p_1(x) = p_2(x) = p(x)$, inasmuch as the pressure is constant both on metal thickness and on bimetal thickness in the considered section x within the considered deformation zone model. It is obvious that it is a necessary but insufficient condition for the task solution.

Therefore, from system of the equations (8) and (9) respectively, we determine the rate of contact border of bimetal with metal $u(x)$ and the general for a two-layer flow process in the deformation zone pressure gradient $\frac{\partial p(x)}{\partial \delta}$ in the form

$$\frac{\partial p(\delta)}{\partial \delta} = \frac{\mu_1 \mu_2 Q_1 g_2 - Q_2 g_1}{f_1 f_2 \frac{\mu_2 g_2}{f_2} - \frac{\mu_1 g_1}{f_1}}, \quad (13)$$

$$u(x) = \frac{\frac{\mu_2 Q_2}{f_2} - \frac{\mu_1 Q_1}{f_1}}{\frac{\mu_2 g_2}{f_2} - \frac{\mu_1 g_1}{f_1}}. \quad (14)$$

Necessary and sufficient conditions of the task solution of analogy dynamics are presented by equality of shear stress on the contact border of the adjoint

$$u(x) \left(\frac{\mu_1}{\ln \frac{c}{b}} + \frac{\mu_2}{\ln \frac{a}{c}} \right) = \frac{1}{4} \frac{\partial p(x)}{\partial x} \frac{(c^2 - b^2) \ln \frac{a}{c} - (a^2 - c^2) \ln \frac{c}{b}}{\ln \frac{c}{b} \ln \frac{a}{c}}. \quad (16)$$

As $u(x)$ and $\frac{\partial p(\delta)}{\partial x}$ are known and are defined from (14) and (15) respectively, the equation (17) should be considered as the equation for determination of the section zones, the adjoint borders of layers $r = c(x)$ at the respective pair flow of bimetal and

$$\begin{aligned} & (\mu_2 Q_2 f_1 - \mu_1 Q_1 f_2) \left(\mu_1 \ln \frac{a}{c} + \mu_2 \ln \frac{c}{b} \right) = \\ & = \frac{1}{4} \mu_1 \mu_2 (Q_1 g_2 - Q_2 g_1) \left[(c^2 - b^2) \ln \frac{a}{c} - (a^2 - c^2) \ln \frac{c}{b} \right]. \end{aligned} \quad (17)$$

From the solution of the equation (17), let us define the nature of border formation of metal and bimetal layers of a bimetallic pipe when pressing on a profile press considering the corresponding coefficients (8) and (9).

zones of bimetal and metal based on a well-known hypothesis of Newton according to [4, 5, 7] in the form:

$$\mu_1 \frac{\partial v_{x1}}{\partial r} \Big|_{r=c(x)} = \mu_2 \frac{\partial v_{x2}}{\partial r} \Big|_{r=c(x)}. \quad (15)$$

Using the expressions (5) and (6) respectively and considering that $p_1(x) = p_2(x) = p(x)$, from the equation (15), we obtain a ratio

metal in the annular deformation zone.

Finally transforming the expression (16), let us write down the necessary equation for determination of interface of bimetal and metal

The nature of change power (dynamic) deformation zone parameters when pressing of bimetallic pipes on a profile press of 16.5 MN is shown in Fig. 4.

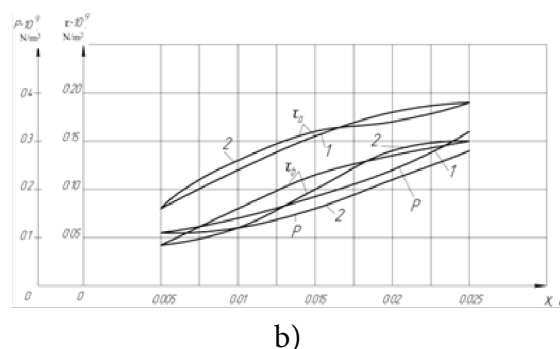
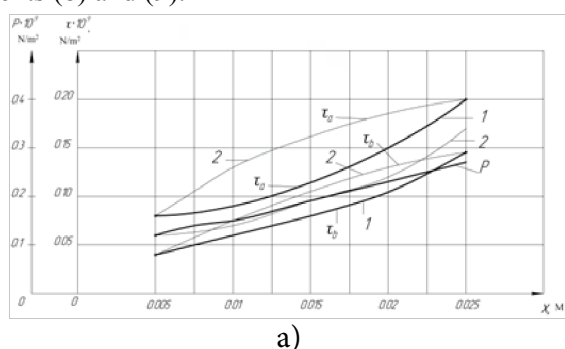


Figure 4. Distribution of pressure and shear stress on mandrel and matrix when pressing of bimetallic pipes of diameter 66×8.0 (billet 135×42.5×400, steel 10 + 0X18H10T): a) $V_0=0.25$ m/s; 1 – tore, 2 – paraboloid; b) $V_0=0.25$ m/s; 1 – cone; 2 – cubic paraboloid.

The analysis in Fig. 4 shows that significant growth in a dynamic component of metal pressure and shear stress is observed throughout the length of deformation zone.

It is necessary to note that the pressure distribution of metal and shear stress on matrix and mandrel of deformation zone depends significantly on the form of the matrix forming a working site, as well as on

parameters ratio of layers and mechanical properties of metal and bimet. Growth of shear stress on a mandrel surface is definitely higher than tension on a matrix that points to characteristic heavy-loaded conditions of processing tools functioning during bimetallic pipes pressing.

The nature of distribution of contact shear stress and metal pressure in the deformation zone indicates the need of a rational choice of parameters of bimet and metal layers and their combinations in the initial billets. Besides, the form of the matrix forming working surface affects significantly the distribution of contact shear stress and metal pressure in the deformation zone. From the analysis of the considered model, it can be seen that the pressing process of bimetallic pipes is implemented the most effectively on a matrix with the generatrix in the form of a cubic parabola.

A certain opportunity for forecasting of technology and working of the real pressing modes of weldless bimetallic pipes is represented by mathematical modeling of pressing processes. It can be noted that modeling of the real modes of bimetallic pipes pressing according to two the most common above-mentioned patterns allows selecting of necessary initial parameters of bimetallic billets, compatible properties of layers and rational geometry of the processing tool for conducting of steady pressing process.

The curves given in Fig. 5 indicate the development of dynamic processes and nature of formation instability of layers borders at the outlet from the deformation zone considering the form of the forming matrix.

Therefore, the pressing process parameters are reached by modeling and selecting of optimum parameters of bimetallic billet at the corresponding stage of technological design. In the future, this provides essential improvement of bimetallic pipes quality. It should be noted that the increase in service durability of processing tools (matrix and mandrel) is provided simultaneously by maintenance of the rational modes of their load.

By the profile press experimental researches [2], it is determined that pressing efforts of bimetallic pipes of diameter 66×8.0 from the centrifugal-cast billet of steel 10 + 0X18H10T, which dimensions are 135×42.5×400, and at heating temperature 980 – 1100 degrees in the range of conic matrixes parameters change with application of glass-lubricant reaches about 8 - 9 MN. The specific pressure during pressing of bimetallic pipes is changed within 420 – 450 $\dot{I} \dot{I} / \dot{i}^2$.

It can be noted that the obtained results indicate some mathematical model inaccuracies of bimetallic pipes pressing process (computational error within 10 – 12%). It requires the research of new opportunities for improvement of existing and development of new effective technologies of bimetallic pipes production of a wide range, and puts forward the relevant tasks of processes mathematical models specification, and raises questions on the processing tool rational design. Thus, it is obvious that, first of all, the optimization task of a working surface parameters of matrix rings is highlighted, inasmuch as the parameters of bimetallic pipes are fixed. This task can be solved by minimization of axial resistance functionality of pressing process.

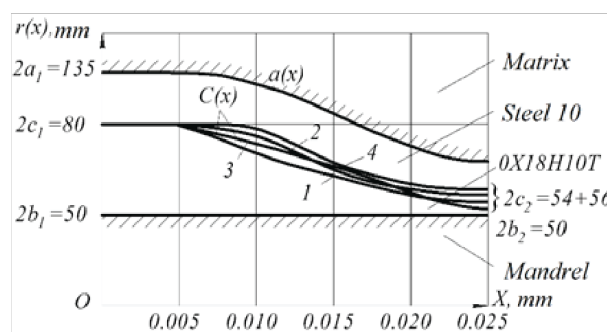


Figure 5. Nature of formation of layers borders in the deformation zone when pressing of bimetallic pipes (billet 135×42,5×400, pipe 66×8.0, steel 10 $\mu_1 = 3,6 \cdot 10^4 \dot{I} \dot{n} / \dot{i}^2$ and 0X18H10T $\mu_2 = 7,2 \cdot 10^4 \dot{I} \dot{n} / \dot{i}^2$; $V_0 = 0.25$ m/s) on a profile press of 31.5 MN using the matrixes with the generatrixes; 1 – sphere, 2 – paraboloid; 3 – cone; 4 – cubic paraboloid.

Conclusions

1. The task solution for a case of axisymmetric, two-layer flow of bimet and metal in the annular space of the deformation zone formed by a matrix and a mandrel within the accepted settlement scheme and the pressed metal rheology is achieved.
2. The parameters of metal and bimet layers, the nature of change of power and dynamic parameters of the deformation zone when bimetallic pipes pressing are established.
3. It is revealed that distribution of shear stress on matrix and mandrel depends significantly on a form of the matrix forming a working site, as well as on the ratio of parameters of metal and bimet layers and their physical and mechanical properties.
4. The forecasting of processes and working of the modes of bimetallic pipes pressing are presented by mathematical modeling of the modes of weldless bimetallic pipes pressing within dynamic model of a task.

5. The assessment of efficiency of the bimetallic pipes pressing modes and reliability of the obtained results of the most common combinations of bimetal and metal layers is carried out.

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