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ESTIMATION OF GLASS LUBRICANT VISCOSITY FOR HOT EXTRUSION OF CR-NI STEEL AND NI ALLOY TUBES

Purpose. Estimation of optimal viscosity of a glass lubricant for chromium-nickel steel tube extrusion depending on the deformation resistance, chemical composition of metal and the temperature, degree and rate of deformation.

Methodology. To determine the force conditions for tube extrusion, a complex factor of deformation resistance was used, which consists in estimating the value of deformation resistance under the basic process parameters of extrusion plants and its refinement depending on the deviations of heating temperature and wall thickness of billets as well as the degree and rate of deformation from the base conditions.

Findings. The dependence of basic values of deformation resistance on the percentage of alloying elements (Ni + Cr) in steels has been found. With the addition of hardening alloying elements (Mo, W, V, Nb) into the alloy steel, its deformation resistance increases in proportion to their percentage. Analytical expressions for calculating the base values of deformation resistance for different extrusion plants have been obtained.

Originality. For the first time, the principles governing estimation of the optimal viscosity of glass lubricants based on the chemical composition of steel to be formed, its temperature and the degree and rate of deformation of the blank, thickness of the lubricating layer and geometric dimensions of the tool (die) in hot extrusion of tubes have been established.

Practical value. The use of the results of calculation according to the developed method will make it possible to increase the surface quality of tubes manufactured by extrusion and reduce the volume of their subsequent machining.

Keywords: *alloying elements, deformation resistance, glass lubricant viscosity, extrusion ratio, extrusion, alloys*

Introduction. In metal forming processes, the force of external friction that arises on the contact surfaces of the deformable body and the tool as a result of their relative motion has a significant effect on the process and the result of plastic deformation.

External friction in metal forming influences the following process parameters:

- diagram of the stress state and deformation resistance of the metal being worked;
- magnitude of the deforming forces;
- quality of the surface of extruded tubes.

Metal working lubricants, which are applied to the contact surface, are an effective means of neutralizing negative effects of external friction during deformation.

Deformation that takes place with low values of external friction forces, thus, minimizes undesirable shearing strain, increases uniformity of the metal flow and improves quality of the surface of extruded tubes.

Today, the most effective metal working lubricant used in metal heat treatment is glass, which is widely used in a number of metal working processes, including hot extrusion process to manufacture steel pipes and tubes [1, 2].

Glass-based lubricants must meet the following basic requirements:

- they must form a seamless lubricating film;
- they must ensure that the extrusion process is carried out under conditions of liquid friction with minimal loads on the tool.

Glass-based materials of grades VP68/1688, VP68/1754, EG6809, EG6800 having a viscosity of 60–200 Pa·s at temperatures from 1050 to 1200 °C are currently used for this purpose. However, lack of clear recommendations on the use of such lubricants, the value of their viscosity in particular, lead to a significant surface quality degradation (flaws, shatter marks) of extruded pipes or tubes.

In this regard, estimation of the optimal viscosity of a glass lubricant for specific conditions of manufacturing tubes of specific steel grades and nickel-based alloys using an extrusion method remains an urgent task.

Literature review. In their works, Manegin Yu. V., Anisimova I. V. (1978), Gulyaev G. I., Pritomanov A. E., et al. (1973) consider glass lubricants from the point of view of hydromechanical problem of a Newtonian viscous fluid flow. It is assumed that the lubricant optimal viscosity is a function of the flow rate of a deformed metal, minimum thickness of the lubricant layer, geometric dimensions of the processing tool and the yield stress of the deformed metal.

The technical literature proposes a number of dependences to estimate optimal viscosity of glass lubricants, a detailed analysis of which is provided in the works by Prozorov L. V. (1969). The issues of modeling a steel tube extrusion process using metal working lubricants are discussed in the works [3, 4].

The authors of the work [2] note that viscosity and fusibility are important parameters of glass lubricants, as they characterize the rate of glass softening and formation of a melt of certain thickness and strength. Therefore, one of the main requirements for a glass lubricant is its granulometric composition, and for the resulting melt – its viscosity. Both parameters determine the effectiveness of lubricating layer formed in the contact area, which can reduce the extrusion force and ensure the required surface quality of the resulting tubes. Our study found that a change in the glass lubricant viscosity reduced the extrusion force more effectively than a change in its particle size. Moreover, a more significant effect on the extrusion force was achieved with correct selection of viscosity of the material for the glass disc than of that to be applied on the inner wall surface of the billet.

The paper [5] considers the issues of rational dosage of glass lubricants where tube extrusion is generally restricted to difficult-to-form steels and alloys. It was found that the lubricant viscosity, along with the deformation temperature, was one of the key determinants of the surface quality of extruded tubes, especially those of chromium-nickel alloys. Notably, glass discs installed on the working surface of an extrusion press die are used as a lubricant. Coming in contact with hot metal, the disc heats up and a liquid phase of the lubricant is formed in the place of contact with metal, which is then carried out by metal from the deformation zone through the die ring. Effectiveness of the lubricant used is determined by its ability to form a thin uniform layer in liquid phase, capable of reliably isolating metal from the die under high normal contact stress.

Thickness of the lubricating film is determined by the liquid phase flow dynamics and the depth of penetration of the glass disc, while its strength is determined by the viscosity of glass lubricant. For alloy steel and stainless steel tube extrusion at a flow rate of up to 4 m/s, the author of work [5] recommends using glass lubricants having a viscosity of 70–100 Pa · s. Such lubricants ensure formation of a strong thin film in the liquid phase at specific pressures up to 1000 MN/m^2. This recommendation is attributable to the fact that there are two countervailing factors that have an effect on the process in this case: with an increase in deformation (extrusion ratio), the heating of metal increases due to deformation and the viscosity of glass lubricant decreases, but at the same time, there is also an increase in the metal flow rate and, consequently, in the rate of lubricant removal from the deformation zone. As a result, the lubricant does not have time to additionally warm up and thus retains the required viscosity.

The use of such lubricants in chromium-nickel steel extrusion, where extrusion ratios are much lower, may cause the formation of defects on the tube surface. This circumstance makes it necessary to determine the relationship between the viscosity of lubricants and the resistance to deformation of extruded steels and alloys [2].

Among the main factors that determine variable parameters of the extrusion process [6], including viscosity of glass lubricants, is the resistance to deformation [7, 8] or the true yield point of metal [9] at the appropriate temperature [10], degree and rate of deformation [11].

Resistance of material to deformation depends on the degree, rate and temperature of deformation, chemical composition of the material, and the nature of development of deformation in time (prehistory of loading) and continuously changes in the process of deformation. Therefore, a true value of resistance of material to plastic deformation is very difficult to determine. As a rule, either statistical data of a real process or empirical dependences obtained as a result of mechanical tests are used for this purpose [12].

The authors of work [13], when specifying the deformation mode of tubes made of corrosion-resistant steels having different nickel content, propose to take into account the impact strength, as well as reduction in diameter (μ_D) and wall thickness (μ_S) by proceeding from the ultimate deformation. In this case, the authors believe that it is rational to carry out deformation at $\mu_D \leq 1.25\mu_S$. The authors take into account the influence of chemical composition of material using coefficients associated with the value of steel impact strength at room temperature. For this purpose, the authors of work [11] propose to use the results of hot torsion tests to measure the degree and rate of deformation in a hot extrusion process.

To determine deformation resistance in most metal forming processes, it is customary to use the "method of thermomechanical coefficients" [14, 15].

Some materials that exhibit complicated rheology, for example, shape-memory alloys such as NiFeGa, do not show good convergence when the data on their deformation resistance are transferred from test results to the extrusion process [16]. Therefore, to determine the rheological behavior of materials in this case, it is necessary to perform experimental extrusion under conditions as close as possible to the actual process.

Shape-memory alloys such as CoNiGa, which show strong anisotropy in the deformed state, require an iterative approach to determining their rheology using both experiments under conditions as close as possible to the actual process, as well as several iterations of computer simulation using the finite element method as presented by the authors in their research paper [17].

According to this method (Tretyakov A.V., Zyuzin V.I. 1973), the basic values of deformation resistance are determined based on tensile testing of samples. The tests are carried out at a metal temperature of ≈ 1000 °C, deformation degree of 0.1 and deformation rate of 10 s^{-1}. The values of these parameters are adjusted using thermodynamic factors, taking into account the actual degree, rate and temperature of metal deformation in a real process, the combination of which makes it possible to obtain an extrusion product without violating the continuity of metal. In this case, the deformation resistance value is calculated by the following formula (Tretyakov A.V., Zyuzin V.I. 1973)

$$\sigma_{true} = k_t \cdot k_\varepsilon \cdot k_u \cdot \sigma_{0S},$$

where σ_{0S} is the basic value of deformation resistance under the abovementioned test parameters; k_t, k_ε, k_u are thermomechanical factors (k_t temperature, k_ε deformation, and k_u rate).

This method is used for calculating force parameters of rolling processes. At the same time, the use of the specified method is not suitable for calculating force processes of hot extrusion of tubes, which differs in the stress state scheme (all-round non-uniform compression, deformation degree of 90 % or higher, metal temperature up to 1250 °C and the deformation rate of 100 s^{-1}).

In this regard, the authors [18] proposed the following formula to calculate the extrusion force for tube extrusion plants

$$P = F \cdot \ln \mu \cdot \rho, \quad (1)$$

where P is the extrusion force, MN; F is a cross-sectional area of the billet in its preloaded state, m^2; μ is an extrusion ratio during tube extrusion; ρ is a proportionality factor that takes into account deformation resistance, geometric shape of the deformation zone, chemical composition of steel, temperature of the workpiece, the degree and rate of deformation during the extrusion process, and the true yield point of metal.

At present, the value of deformation resistance included in (1) is an approximate figure, since it is determined with the values of temperature, degree and rate of deformation that do not correspond to an actual extrusion process. The use of these data in real production is often a reason that does not allow achieving optimal conditions for the production of tubes through an extrusion process and a quality that would meet the regulatory requirements (GOST, TU, and others)

Purpose. The purpose of this paper is to estimate the optimal viscosity of a glass lubricant depending on the deformation resistance, chemical composition of metal, and temperature, rate and degree of deformation, which make it possible to set the required force parameters of steel tube extrusion under the given processing conditions.

Methods. In this paper, the deformation resistance value ρ for tube extrusion (Fig. 1) is proposed to be calculated using the following formula [18]

$$\rho = \rho_0 \cdot K_{T.S} \cdot K_\mu \cdot K_{\dot{\varepsilon}}, \quad (2)$$

where ρ_0 is the deformation resistance under basic conditions for each extrusion plant, MN/m^2; $K_{T.S}$ is a factor that takes account of the discrepancy between the heating temperature and wall thickness of billets and their base values; K_μ is a factor that takes account of the deviation of deformation degree (extrusion ratio) from its base values; $K_{\dot{\varepsilon}}$ is a factor that takes account of the discrepancy between the deformation rate and base values.

The following parameters define basic conditions for various extrusion units used to extrude stainless steels and nickel and titanium alloys: temperature of heating a billet in the furnace (T), wall thickness of the billet (S), diameter of the container liner (D_k), and the blank transportation time during the extrusion process (τ). Their values are given in Table 1.

Results. ***Defining the*** ρ_0**.** Deformation resistance of steels and alloys essentially depends on their alloying degree (Tretyakov A. V., Zyuzin V. I. 1973). Deformation resistance of alloys of the Fe–Ni–Cr system increases monotonically with an increase in the Ni and Cr content in such alloys, as presented in the work by F. F. Khimushin (1957), which follows from the dependence shown in Fig. 2.

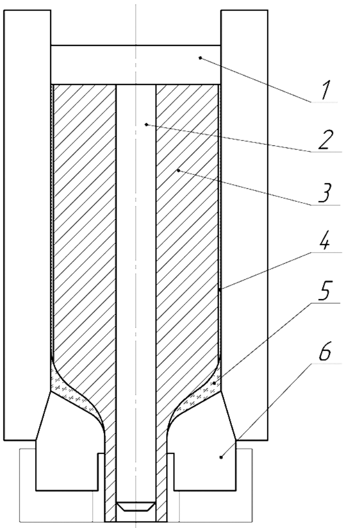

Fig. 1. Schematic of tube extrusion:

1 – dummy block; 2 – mandrel; 3 – billet; 4 – glass lubricant on the contact surface of container liner; 5 – lubricating disc; 6 – die

Table 1

Parameters of the basic conditions for the extrusion of steels and alloys on an extrusion plant

Extrusion plant force, MN	τ, s	D_k, mm	S, mm	T, °C
16.0	39	190	50	1150
20.0	98	195	50	1200
55.0	125	341	80	1200

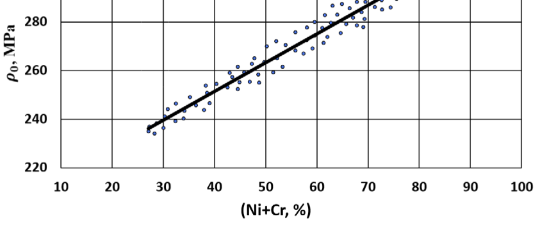

Fig. 2. Dependence of deformation resistance ρ_0 on the total amount of Ni and Cr in steel and nickel alloys

The dependence in Fig. 2 was obtained on the basis of statistical processing of measurements of the force required for extrusion of more than 30 grades of steels and alloys (12Х18Н10Т, ХН32Т, ХН45Ю, ХН78Т, ХН40Б, Х23Н28МДТ and others) under the following basic conditions: D_k = 195 mm, S = 50 mm, T = 1150 °C, extrusion ratio μ = 7–10.0.

Based on the results of statistical processing of production data, the following equation was obtained

$$\rho_0 = 200 + 1.2 \cdot (\mathrm{Ni} + \mathrm{Cr}), \tag{3}$$

where Ni, Cr is the content of nickel and chromium in the alloy, % (by mass).

Mo, W, V, and Nb alloying also increases deformation resistance of steel in proportion to the mass content of alloying elements. In this regard, equation (3) can be presented as follows

$$\rho_0 = 200 + 1.2 \cdot (\mathrm{Ni} + \mathrm{Cr}) + \alpha \cdot (\mathrm{Mo} + \mathrm{W} + \mathrm{V} + \mathrm{Nb}), \tag{4}$$

where α is the proportionality factor; Ni, Cr, Mo, W, V, Nb is the mass fraction of chemical elements, %.

During extrusion of tubes in the above alloys with diameters ∅76–168 mm and wall thickness S = 10–20 mm on a 16 MN and 20 MN extrusion press; ∅133–245 mm and wall thickness S = 14–30 mm on a 55 MN extrusion press it was found that the value of proportionality factor (α) was 2.0 with the total content of alloying elements (Mo + W + V + Nb) in steel up to 10 %, and with their total content greater than 10 % α was equal to 6.5, which is explained by hardening of the metal due to additional phases in its structure.

Comparison of the estimated and experimental values shows that deviation of the estimated values of deformation resistance from their actual values does not exceed 10 MPa (the error is less than 5 %), which makes it possible to recommend (4) for engineering calculations.

Defining the $K_{T.S}$. Temperature has the greatest impact on deformation resistance. The value of the factor that takes account of the effects of heating temperature and wall thickness is calculated using the following formula [18]

$$K_{T.S} = e^{m \cdot (T_0 - T_H - \Delta T_0 + T_{ST})},$$

where T_0 is the base heating temperature of a billet for each extrusion blank, °C; T_H is the heating temperature of billets, °C; ΔT_0 is the change in billet temperature during the cooling process in the course of auxiliary operations under basic conditions for each extrusion plant; $\Delta T_{S,T}$ is the change in billet temperature during the cooling process in the course of auxiliary operations, taking into account the deviation of wall thickness and heating temperature of billets from basic conditions; m is the exponent, the values of which are given in Table 2.

Based on the foregoing, it is recommended to calculate $K_{T.S}$ for extrusion plants operating under basic conditions given in Table 1 using the following formulas:

- for 16.0 MN extrusion press

$$K_{T.S} = e^{0.87 \cdot m \cdot \left(\frac{4146}{S} + 1065 - T_H\right)};$$

- for 20.0 MN extrusion press

$$K_{T.S} = e^{0.72 \cdot m \cdot \left(\frac{8330}{S} + 1036 - T_H\right)};$$

- for 55.0 MN extrusion press

$$K_{T.S} = e^{0.76 \cdot m \cdot \left(\frac{11320}{S} + 1053 - T_H\right)}.$$

From the analysis of the data in Table 2 it can be seen that the m values vary within significant limits and depend on the experimental technique described in the works by A. V. Tretyakov, V. I. Zyuzin (1973). The analysis also reveals the dependence of the m value on the degree of high-temperature strength of the alloy, which is consistent with the very nature of high-temperature strength.

Table 2

Values of exponent *m*

Steels and alloys	*m* values		
	A. V. Tretyakov (1973)	T. Shpittel (1982)	Recommended by authors
Austenitic steels, including those stabilized with Nb, Ti, and so on	0.0028	0.00284	0.0040
Austenitic stainless steels containing more than 2 % Mo	–	–	0.0034
Ni–Cr–Fe alloys with Ni content = 20–45 %, unhardened	–	0.0022	0.0032
Ni–Cr–Fe alloys with hardening elements up to 5 %	0.0032	0.0023	0.0030
Ni–Cr alloys, unhardened	0.0032	0.0023	0.0028
Ni–Cr alloys with hardening elements up to 10 %	–	0.0020	0.0025
Ni–Cr alloys containing more than 10 % of hardening elements	0.0028	0.0030	0.0022

Values recommended by the authors in this paper are based on the results of statistical studies, for various extrusion plants, the classification of alloys in Table 2 is conditional. Nevertheless, the error in *m* assessment for a particular alloy using the data in Table 2 does not exceed 5 %.

Defining the K_μ. The effect of deformation degree on deformation resistance is rather ambiguous. In the process of reaching high degrees of deformation characteristic of extrusion, deformation resistance undergoes several stages that are fundamentally different from each other. At the initial stage, it continuously increases until the pressing degree reaches 30–35 %. After reaching its maximum value, deformation resistance begins to decrease sharply as a result of the influence of metal heating. This tendency is convincingly demonstrated by the data shown in Fig. 3.

The effect of deformation degree ρ on deformation resistance expressed as the extrusion ratio during the extrusion process was investigated during experimental-industrial extrusion of 12X18H10T stainless steel tubes with a standard diameter of ∅89–159 mm and a wall thickness of S = 4.5–11 mm within a billet temperature range of 1150–1300 °C. The results are presented as dependences $\rho = f(\mu)$ in Fig. 3.

From the analysis of the course of dependencies in Fig. 3, it can be seen that when the extrusion ratio reaches μ = 5–15, a sharp decrease in ρ begins as a result of metal heating due to the deformation process.

This decrease almost stops when μ = 15 is reached, after which the deformation resistance is virtually independent of deformation degree, which is explained by the prevailing effect of metal heating in the deformation zone. A similar character of changes in the ρ value is observed during extrusion of nickel- and titanium-based alloy tubes [18].

As a rule, extrusion plants produce stainless steel, nickel- and titanium-based alloy pipes and tubes with an extrusion ratio of μ > 10, and we therefore take K_μ as equal to 1.

Defining the $K_{\dot{\varepsilon}}$. The effect of deformation rate on deformation resistance can be estimated with sufficient accuracy from the following formula

$$\rho = \rho_0 \cdot K_{\dot{\varepsilon}} = \rho_0 \cdot \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^n, \qquad (5)$$

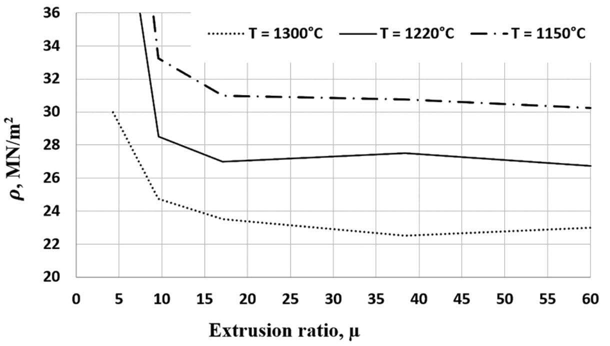

Fig. 3. Dependence ρ *as a function of extrusion ratio* μ *during extrusion of 12X18H10T steel tubes and their initial temperature*

where ε and $\dot{\varepsilon}_0$ are the deformation rates for the current and basic conditions of extrusion, respectively; *n* is an exponent, whose value is determined by the hardening process of a particular material and is determined experimentally.

It is recommended to determine the average deformation rate during tube extrusion by the formula of L. A. Shofman (1961)

$$\dot{\varepsilon} = \frac{6 \cdot U_{av} \cdot \ln \mu}{D_k},$$

where U_{av} is the average velocity of the extrusion ram, mm/s; D_k is the diameter of the tool stem container, mm.

Difficult-to-form alloys are, as a rule, extruded at low pressing speeds (ram velocity) U_{av} = 100–200 mm/s and in a relatively narrow range of the extrusion ratio (μ = 5–15). For these conditions, (5) may be presented as follows

$$\rho = \rho_0 \cdot \left(\frac{D_{k0}}{D_k} \right)^n.$$

The strain hardening exponent *n* depends on the particular material and is determined experimentally. According to the data provided in the work by A. V. Tretyakov, V. I. Zyuzin (1973), for stainless steels at high temperatures *n* = 0.087, for nickel-based alloys *n* = 0.098. The results of processing measurements of extrusion forces at 16, 20 and 55 MN extrusion plants showed that the *n* value for stainless steel and nickel alloy tubes equaled 0.18.

Such a difference between the *n* values and the results presented in the works by Manegin Yu. V., Pritomanov A. E. (1980) is explained by higher degrees of deformation (more than 90 %) during tube extrusion.

Thus, our studies and processing of statistical data have identified all constituents of the deformation resistance dependence (2) on the chemical composition of material and the temperature, rate and degree of deformation, which make it possible to determine the process parameters for steel and nickel alloy tube extrusion with a sufficiently high degree of accuracy.

To estimate optimal viscosity of a glass lubricant for tube extrusion, the technical literature [1–3] considers the hydromechanical problem of the flow of a Newtonian viscous fluid in a converging channel. In this case, the optimal viscosity value is directly proportional to the lubricant film thickness and deformation resistance of metal and is inversely proportional to the rate of flow of the extruded product (Prozorov L. V., 1969).

Taking into account (2), the dependence of optimal viscosity of the glass lubricant was presented as follows

$$\eta_{opt} = \frac{1.4 \cdot h_{\min}^3 \cdot \rho_0 \cdot k_{TS} \cdot k_\mu \cdot k_{\dot{\varepsilon}}}{u_{def.} \cdot r} \times$$

$$\times \left[\frac{2 \cdot l_{pl} \cdot \left(D_T^2 + d_u^2 \right)}{D_T \cdot \left(d_k^2 + d_u^2 \right)} + \frac{1.225 \cdot D_k}{\mu \cdot \Phi \cdot \left(D_k + d_u \right)} \cdot \ln \frac{D_k - d_u}{D_T - d_u} - 1 \right],$$

where h_{min} is the minimum thickness of the lubricant layer, μm; $h_{min} \geq R_z + R_{zM} + 5$, μm; R_z is the roughness of the container liner surface, μm; R_{zM} is the die surface roughness, μm; u_{def} is the rate of deformation, mm/s; r is the die rounding radius, mm;

$$\Phi = \sqrt{\alpha + \frac{3\tan^3\alpha}{2\left(R_T - r_u\right)}},$$

where α is the die taper angle (for flat dies α = 90°); R_T is the tube radius, mm; r_u is the mandrel radius, mm; D_k is the press container diameter, mm; μ is the extrusion ratio; l_{pl} is the height of the die parallel land, mm.

$$\mu = \frac{D_k^2 - d_u^2}{D_T^2 - d_u^2},$$

where d_u is the mandrel diameter, mm.

Conclusions.

1. The paper describes all constituents of the dependence of optimal viscosity on the chemical composition of metal to be formed, and the temperature, degree and rate of deformation, which make it possible to determine the process parameters for tube extrusion of various materials.

2. It was found that the value of proportionality factor (α) was 2.0 with the total content of alloying elements (Mo + W + + V + Nb) in steel up to 10 %, and with their total content in steel greater than 10 %, *α* was equal to 6.5.

3. It was found that the strain hardening exponent *n* for stainless steel and nickel-based alloy tubes extruded at 20 and 55 MN extrusion plants equaled 0.18.

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Визначення оптимальної в'язкості склозмазок при гарячому пресуванні труб із хромонікелевих сталей і нікелевих сплавів

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Мета. Визначення оптимальної в'язкості склозмазки в залежності від опору деформації, хімічного складу металу, температури, швидкості та ступеня деформації при пресуванні труб із хромонікелевих сталей.

Методика. Для визначення силових умов пресування труб використовували узагальнений показник опору деформації, що полягає у визначенні величини опору деформації при базових значеннях параметрів пресових установок і його уточнення в залежності від відхилень температури нагріву й товщини стінки гільз, ступеня та швидкості деформації від базових умов.

Результати. Встановлена залежність базових значень опору деформації від процентного вмісту легуючих елементів (Ni + Cr) у сталях. При введенні до сплавів зміцнюючих легуючих елементів (Mo, W, V, Nb), опір деформації підвищується пропорційно їх процентному вмісту. Отримані аналітичні вирази для розрахунку базових значень опору деформації для різних пресових установок.

Наукова новизна. Уперше встановлені закономірності для визначення оптимальної в'язкості склозмазок від хімічного складу сталі, що деформується, її температури, ступеня та швидкості деформації заготовки, товщини мастильного шару й геометричних розмірів інструменту (матриці) при гарячому пресуванні труб.

Практична значимість. Використання результатів розрахунку розробленої методики дозволить підвищить якість поверхні пресованих труб і скоротити обсяг їх подальшої механічної обробки.

Ключові слова: *легуючі елементи, опір деформації, в'язкість склозмазки, коефіцієнт витяжки, пресування, сплави*

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