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***Medvedev M. I.*[1,*], *Bobukh O. S.*[2], *Kuzmina O. M.*[3],**
***Krasiuk A. D.*[4], *Ivanova L. K.*[5]**

Heat balance of billets during hot extrusion of nickel alloy pipes

[1] ORCID: 0000-0002-1230-420X. Ukrainian State University of Science and Technologies, Ukraine
[2] ORCID: 0000-0001-7254-3854. Ukrainian State University of Science and Technologies, Ukraine
[3] ORCID: 0000-0003-0794-0583. Ukrainian State University of Science and Technologies, Ukraine
[4] ORCID: 0009-0009-8354-687X. CENTRAVIS PRODUCTION UKRAINE PJSC Ukraine
[5] ORCID: 0000-0002-5997-610X. Ukrainian State University of Science and Technologies, Ukraine
*Email: medvedev4747@gmail.com

***Медведєв М. І.*[1], *Бобух О. С.*[2], *Кузьміна О. М.*[3],**
***Красюк А. В.*[4], *Іванова Л. Х.*[5]**

Тепловий баланс заготовок під час гарячої екструзії труб з нікелевого сплаву

[1] ORCID: 0000-0002-1230-420X. Український державний університет науки і технологій, Україна
[2] ORCID: 0000-0001-7254-3854. Український державний університет науки і технологій, Україна
[3] ORCID: 0000-0003-0794-0583. Український державний університет науки і технологій, Україна
[4] ORCID: 0009-0009-8354-687X. ПРАТ «СЕНТРАВІС ПРОДАКШН ЮКРЕЙН», Україна
[5] ORCID: 0000-0002-5997-610X. Український державний університет науки і технологій, Україна
*Email: medvedev4747@gmail.com

Abstract. *One of the main problems in the production of nickel-based alloy pipes by hot extrusion on horizontal hydraulic presses is the high level of surface defects. A key factor influencing defect formation is the temperature variation of the billet throughout the technological process. The aim of this work is to establish the regularities of temperature changes in nickel alloy pipe billets during the main stages of production on presses with forces of 16.0 MN and 31.5 MN using glass lubricants.* ***Methodology****. The study is based on a systematic analysis of the industrial process of hot extrusion of pipes from nickel alloy 602CA. The main stages considered include billet transportation, application of glass lubricant, transfer to the press, holding in the container, and extrusion. Temperature losses at each stage were determined using analytical and empirical equations based on thermographic measurements.* ***Results****. It was found that the total temperature drop of billets during auxiliary operations is inversely proportional to the wall thickness. Within the range of 40–120 mm and heating temperatures of 1050–1250 °C, this dependence is close to linear.* ***Scientific novelty****. A methodology for calculating billet temperature at the main stages of preparation for extrusion has been developed for the first time.* ***Practical utility.*** *The proposed approach enables a justified selection of glass lubricants according to actual temperature conditions, which improves the surface quality of pipes, reduces rejection rates, and decreases the amount of subsequent machining.*

Keywords. *hot extrusion, nickel-based alloys, pipe billets, heat balance, temperature field, cooling, glass lubricant, seamless pipes*

Анотація. *Однією з основних проблем при виробництві труб із нікелевих сплавів методом гарячого пресування на горизонтальних гідравлічних пресах є високий рівень поверхневих дефектів. Ключовим чинником їх утворення є зміна температури заготовки протягом усього технологічного процесу. Метою роботи є встановлення закономірностей зміни температури трубних заготовок із нікелевих сплавів на основних етапах виробництва труб на пресах із зусиллям 16,0 МН і 31,5 МН із використанням склозмазок.* ***Методика****. Дослідження базується на системному аналізі промислового процесу гарячого пресування труб зі сплаву 602СА. Розглянуто основні етапи: транспортування заготовки, нанесення склозмазки, подача до преса, витримка в контейнері та пресування. Поетапні втрати температури визначали з використанням аналітичних і емпіричних залежностей, отриманих за результатами термографування.* ***Результати****. Встановлено, що сумарне зниження температури заготовок під час допоміжних операцій обернено пропорційне товщині їх стінок. У діапазоні товщин 40–120 мм і температур нагріву 1050–1250 °С ця залежність є близькою до лінійної.* ***Наукова новизна.*** *Вперше розроблено методику розрахунку температури заготовок на основних етапах їх підготовки до процесу пресування.* ***Практична значущість****. Запропонований підхід дозволяє обґрунтовано обирати склозмазки з урахуванням реальних температурних умов процесу, що забезпечує підвищення якості поверхні труб, зниження рівня браку та скорочення обсягів подальшої механічної обробки.*

Ключові слова: *гаряче пресування, нікелеві сплави, трубні заготовки, тепловий баланс, температурне поле, охолодження, склозмазка, безшовні труби*

Introduction. The rapid development of technology, the mining industry, and nuclear energy is inextricably linked to the use of pipes made of complex alloy steels and nickel- and iron-nickel-based alloys with enhanced operational properties (heat resistance, heat strength, fatigue strength, wear resistance, etc.) [1,2]. Today seamless pipes made of nickel alloys account for about 30% of the global market for such products.

In the cast state, billets from such alloys, according to the classification of the work [3], are classified as group B6. That is, in the cast state, these are extremely brittle alloys, the processing of which by pressure can be performed in one or two types only in the hot state, only under certain conditions - at an extremely low speed and a small degree of one-time deformation of the billet of limited dimensions and simple configuration.

This conclusion is confirmed by the results of many studies [4,5] and production practice of the product [6,7], from which it follows that with the improvement of technological and operational characteristics, high alloying of alloys contributes to an increase in their resistance to deformation and a decrease in technological plasticity. In turn, this contributes to a significant reduction in the temperature range of achieving maximum plasticity and high deformation heating [8,9], which leads to the impossibility of rolling these alloys. When producing pipes from such materials on roller pipe rolling plants, several technological problems arise, associated with the occurrence of violations of the continuity of the metal of the product [10,11].

Today, the only industrial method of manufacturing high-quality products from such alloys, in particular pipes, is the method of hot extrusion using glass lubricants. At the same time, for the successful implementation of the process of hot extruded pipes and minimizing the level of their defects, it is necessary to select the temperature of maximum plasticity of the deformed alloy and maintain the optimal temperature balance at all stages of its implementation [12, 13]. The temperature of maximum plasticity when extruded pipes with high accuracy for a number of nickel alloys can be selected according to the results of work [14, 15], which are shown in Fig. 1-3.

The alloys shown in Fig. 1-3 belong to the groups of nickel- and iron-nickel-based alloys according to GOST 5632-72 and standards DIN 2.4631, 2.4856, 2.4858; AISI/SAE N07080, N 06625, N06626 N08825.

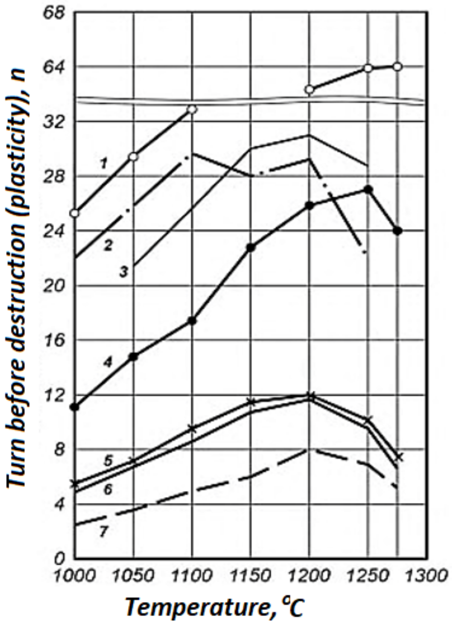

Figure 1 – Temperature ranges of maximum plasticity based on hot torsion test results for alloys: 1 – KhN78T (Ni–Cr alloy with Ti); 2 – KhN77TYuR; 3 – 12Kh18N10T (similar to AISI 321 / EN 1.4541); 4 – KhN70V; 5 – KhN70Yu; 6 – KhN60VT.

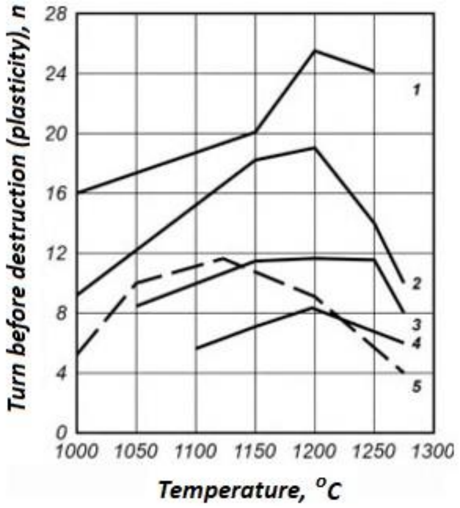

Figure 2 – Temperature ranges of maximum plasticity based on hot torsion test results for alloys: 1 – KhN45MKTYuB; 2 – 06Kh23N28MDT; 3 – KhN45MBTs; 4 – KhN40MDTYu; 5 – KhN55MBTs; 6 – 03Kh20N32M3B.

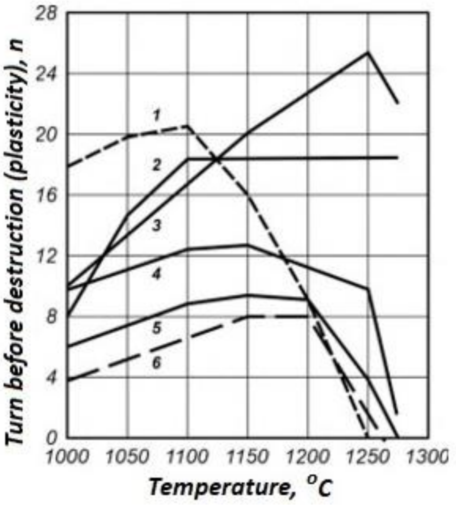

Figure 3 – Temperature ranges of maximum plasticity based on hot torsion test results for alloys: 1 – KhN45MKTYuB; 2 – 06Kh23N28MDT; 3 – KhN45MBTs; 4 – KhN40MDTYu; 5 – KhN55MBTs; 6 – 03Kh20N32M3B.

Solving the problem of frequent shortages of pipes made of such alloys in production is usually hindered by the lack of data on the magnitude and nature of the change in the temperature of the sleeves at the preparatory and transport stages of the deformation process on press installations. Such problematic issues arise on installations with presses with a force of 16.0 MN and 31.5 MN, for which there is currently no information on the rational choice of glass lubricants for the surfaces of the workpiece. The need for these data is explained by the fact that the glass lubricants currently available "work" well only in a limited temperature range (the temperature of heating the workpiece for extrusion), which is not constant at different stages of the technological process and places of their use, which, in particular, follows from the analysis of the data in Table 1 for glass lubricants "Pemco" [9].

Table 1 – Temperature conditions for Pemco glass lubricants.

Glass lubricant	Temperature of billet, °C	Use of glass lubricants in the technological process
VP68/1688	1060-1085	Rolling of billets and sleeves
VP68/1673	1135-1170	Rolling of billets and sleeves
VP68/1754	1100±20	Rolling of billets and sleeves
EG6800	1135-1170	Inside the sleeves, glass washers
EG6809	1085-1135	Inside the sleeves, glass washers (mix 6809 i 6800)
EG6826	1015-1085	Inside the sleeves, glass washers
VP68/2900	1080-1180	Into the cone of billet
	1080-1140	Inside the sleeves
EG6807	1080-1180	Into the cone of billet

As a result, unstable temperature conditions during the cooling of the billet at the stages of its preparation for pressing and the use of an irrationally selected glass lubricant for this purpose lead to defects in up to 80% or more of the pipes manufactured at the enterprises.

In this regard, work devoted to establishing the patterns of temperature change in nickel alloy pipe billets during the main stages of pipe production, which are manufactured by extrusion them on presses with a force of 16.0 MN and 31.5 MN, allowing the selection of a rational glass lubricant, is relevant.

State of the problem. Today, the only possible method of manufacturing pipes from hard-to-deform alloys, implemented in industrial conditions, is hot extrusion with glass lubricant, which is implemented according to the scheme of stress state of comprehensive uneven compression. This method allows for a sharp increase in the plasticity of the alloy, which makes it possible to apply large single-stage deformations of the material.

Currently, the hot extrusion method is the basis for installations with a horizontal hydraulic press, the working unit diagram of which is shown in Fig. 4.

Hot extrusion is mainly used to produce pipes from high-alloy steels and alloys; however, when the alloy lacks sufficient plasticity [6], defects appear on the pipe surfaces, the appearance of which is shown in Fig. 5.

An analysis of the quality of pipes manufactured in industrial conditions shows that the most common defects on the surface of pipes made from these alloys are transverse tears and cracks – typical defects on the outer and inner surfaces of pipes, which are localized breaks in the metal, oriented across the pipe axis along its entire perimeter and length. At the same time, the degree of development of these defects is greater on the inner surface than on the outer surface, which is due to the difference in deformation conditions [15].

Transverse tears and cracks are the result of reduced alloy plasticity due to its nature. To prevent this defect, the plasticity of the alloy is increased by:

- selecting and maintaining the temperature range of maximum plasticity, reducing its initial temperature for this purpose;
- limiting the degree of deformation; creating counterpressure in the matrix by performing an elongated or conical (with a small taper angle) calibrating belt in it or installing plastic shells on the surface of the workpiece.

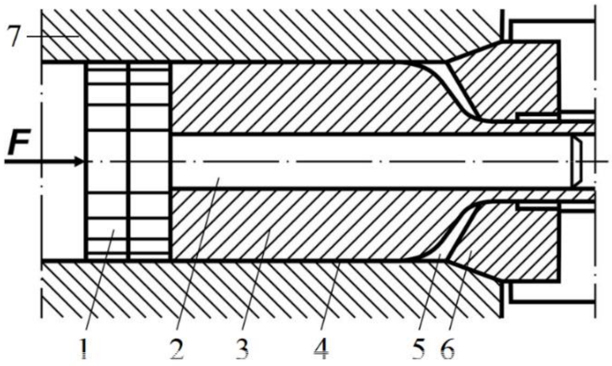

Figure 4. Diagram of the working unit of the installation with a horizontal hydraulic press: 1 – press washer; 2 – mandrel; 3 – sleeve; 4 – glass lubricant on the contact surface of the metal container; 5 – lubricating washer; 6 – die; 7 – container.


a b

Figure 5. Appearance of defects (breaches in integrity) on the inner surface of the pipe:
a – longitudinal cracks; b – rough ‘ripples’.

As a result, achieving a positive result in terms of improving the surface quality of pipes in these cases is accompanied by a sharp increase in labour intensity, time and financial costs of production.

Achieving high levels of performance characteristics of alloy 602CA after hot extrusion is only possible when it is deformed in a relatively ‘narrow’ temperature range (1080...1100 °C) [6]. Fulfilling this condition is crucial for ensuring the homogeneity of the alloy microstructure and preventing defects that could affect the performance characteristics of the products [9, 10]. In addition, maintaining the required temperature regime for hot extrusion minimizes the likelihood of surface defects such as cracks, porosity and local hardening, which improves the quality of the final product [11, 12].

Based on this, the rational temperature range for hot extrusion can be represented by the following inequality [16]:

$$T_{\min} \le (T_0 \pm \Delta T) \le T_{\max}, \tag{1}$$

where T_{min} is the minimum permissible temperature, which depends both on the load on the pipe extrusion equipment and on the susceptibility of the microstructure to dynamic recrystallisation, °C [13]; T_0 is the heating temperature in the heating device; ΔT is the resulting temperature change caused by both heat generation due to deformation (+) and heat loss during transportation of the sleeve from the heating device to the pipe press (-), °C; T_{max} – maximum sleeve temperature [14] at which grain boundaries in the alloy begin to melt, °C.

The known data on nickel alloy 602CA during its deformation, presented from the point of view of microstructural transformations [15], raise doubts about their reliability with regard to the value of ΔT in inequality (1). The development of finite element modelling of the extrusion process of nickel alloys is mainly focused on the deformation process from the moment the pipe begins to be pressed, which does not allow the value of ΔT in inequality (1) to be calculated [16,-18].

Currently, there is no method for calculating the temperature of the sleeve during the preparatory period of its extrusion on press installations with presses with a force of 16.0 MN and 31.5 MN. This circumstance does not allow determining rational thermo-time parameters. That is, the solution to the problem of ensuring a consistently high quality of the surface of pressed pipes, while reducing labor, time and financial costs of production, is to maintain a rational temperature of the sleeves at all stages of their preparation for extrusion in order to select a rational glass lubricant for their surfaces.

One way to achieve this goal is a comprehensive analytical step-by-step solution to the problem, which is currently lacking in relation to the technology of extruded pipes on installations with presses with a force of 16.0 MN and 31.5 MN.

The aim of the work is to establish the patterns of temperature change in nickel alloy pipe billets at the main stages of pipe production, as well as how they are manufactured by extrusion them on presses with a force of 16.0 MN and 31.5 MN with glass lubricant.

Research methodology. The methodology included a systematic analysis of the existing technological process to produce hot-extruded pipes from nickel alloy 602CA on press units with horizontal hydraulic presses with a force of 16.0 MN and 31.5 MN. The main technological stages included:

1. transportation of the billet (sleeve) from the induction heater to the glass lubricant application table;
2. application of glass lubricant to the surface of the billet;
3. transporting the workpiece with glass lubricant to the press;
4. holding the workpiece in a container before pressing;
5. pressing in a container.

The duration of the above technological stages was determined by recording them with a stopwatch under real production conditions for hot-pressed pipes on the above-mentioned installations.

The chemical composition of the billets was determined using an Elvax plus spectrometer.

The thickness of the glass lubricant layer on the surface of the billet after completion of its expansion was determined after cooling the lubricant layer chips to room temperature using a vernier caliper with an accuracy of 0.01 mm.

The temperature of the outer surface of the billet was determined by thermography using chromel-alumel thermoelectrodes in combination with an electronic potentiometer.

The quality control of the manufactured pipes for compliance with regulatory and technical documentation was carried out visually.

For the analytical description of the process under consideration, both known and our own analytical and semi-empirical equations were used, which are given in [15].

Since the cooling of the billets in the technological chain under consideration occurs through heat transfer by thermal conductivity and radiation into an environment with a constant temperature, and the cooling time of the billets is relatively short, the heat transfer process does not have time to reach a steady state. In this regard, the change in the temperature of the workpiece during the preparatory stages of pressing can be calculated using the formula given in the work of Dzyuzer V. Ya. (2016):

$$m \cdot C_m \cdot \Delta T = A \cdot \bar{q} \cdot \tau \ , \tag{2}$$

where *m* is the mass of the workpiece, kg; C_m is the specific heat capacity of the alloy, in J/(kg·K); ΔT is the change in the temperature of the workpiece, °C; A is the cooling area of the workpiece, m^2; $\bar{q}$ is the average heat flux from the surfaces of the workpiece, W/m^2; *τ* is the cooling time of the workpiece.

Transportation of the workpiece (sleeve) from the induction heater to the glass lubricant application table.

The temperature change at this stage during its duration τ_1 was calculated using the following converted equation:

$$\Delta T_1 = \frac{3{,}6 \cdot A \cdot \bar{q} \cdot \tau_1}{m \cdot C_m}. \tag{3}$$

Analysis of equation (3) shows that the change in body temperature during cooling is directly proportional to the specific cooling surface area - A/m, which for a solid cylindrical body is inversely proportional to its radius. If cooling from the inner surface of a hollow cylinder can be neglected in this case, then to account for heat loss through its ends, the end radiation area (cross-sectional area of the cylinder opening) must be increased by 25%. In this case, equation (3) will look like this:

$$\Delta T_1 = \frac{7{,}2 \cdot k_G \, \bar{q} \cdot \tau}{C_m \cdot \gamma \cdot t}, \tag{4}$$

$$k_G = \frac{1+0{,}625\frac{d}{D}\cdot\frac{d}{l}}{1+\frac{d}{D}},$$

where *γ* is the density of the alloy; *t* is the wall thickness of the billet *D*; d is the outer and inner diameters of the hollow billet, respectively; *l* is the length of the billet.

The average heat flux, which is the amount of heat released per unit of surface area per unit of time, and the heat transfer coefficient from the surface of the billet to the environment were calculated using the formulas of Gusovsky V.L. (2004):

$$\bar{q} = \alpha \cdot (T_0\text{-}20), \tag{5}$$

$$\alpha = 145.1 \cdot \left(\frac{T_0}{1000}\right)^2 . \tag{6}$$

Based on the results of the measurements, it was established that the thickness of the glass lubricant layer on the billets is 0.1…0.2 mm. In this case, the heat transfer coefficient (α_{GL}) will be as follows:

$$\alpha_{GL} = \frac{1}{\frac{t_{GL}}{\lambda_{GL}}+\frac{1}{\alpha}}, \tag{7}$$

where t_{GL} is the thickness of glass lubricant on the surface of the workpieces after processing, m; λ_{GL} is the specific thermal conductivity of glass lubricant, W/(m·K) (for calculations, λ_{GL}=930 W/(m·K) was assumed).

Equations (4)...(7) are applicable in the case of glass lubricant on the surface of the workpiece.

Application of glass paste to the surface of the workpiece.

The calculation of the temperature decrease (ΔT_2) during contact of the workpiece with cold glass paste with a density of 1500 kg/m^3, specific heat capacity of 840 J/(kg K) and thickness of 0.5 mm was performed using the empirical equation:

$$T_2 = 0.24 \cdot \frac{T_0 - \Delta T_1}{t} . \tag{8}$$

In equation (8), the value ΔT_1 is calculated using equation (4).

Transporting the billet with glass lubricant to the press.

At this stage, the temperature loss ΔT_3 was calculated using equation (4), considering the current thickness of the lubricant layer, calculated using equation (7).

Holding the billet in the container before pressing.

When the billet is placed in the container, air gaps are formed between the billet and the container, as well as the needle. In this case, the temperature loss ΔT_4 can be calculated using equation (4), considering the current thickness of the lubricant layer in equation (7), and representing equations (5) and (6) in the following form:

$$\bar{q} = \alpha \cdot (T_0 - \Delta T_1 - \Delta T_2 - \Delta T_3\text{-}400), \tag{9}$$

$$\alpha = 203.5 \cdot \left(\frac{T_0 - \Delta T_1 - \Delta T_2 - \Delta T_3}{1000}\right)^{1.7}, \tag{10}$$

where 400 is the container temperature, °C; 203.5 and 1.7 are empirical coefficients.

Pressing in a container.

During pressing, the air gaps between the outer surface of the workpiece and the inner sleeve of the container are filled with metal. Therefore, heat transfer from the workpiece to the container is carried out only by thermal conductivity through the glass lubricant layer. Assuming that under the action of normal contact stress during pressing, the thickness of the glass lubricant layer will be 0.25 mm, the value of K_G in equation (4) can be calculated using the equation:

$$K_G = \frac{\lambda_{sm}}{l_{sm}} = \frac{0.93 \cdot 1000}{0,25} \approx 3720 \qquad (11)$$

The mass of the container relative to the mass of the shells can be considered infinite, so the temperature of the container will not change significantly during pressing, which allows it to be taken as constant and equal to 400 °C. In this case, there will be a heat flow from the outer surface of the shells equal to:

$$q = K_G \cdot (T - 400) \qquad (12)$$

To assess the effect of heat flow on the needle, we used the average calorimetric temperature of the system developed by A.I. Veynik (1975), which allows the heating and cooling of any bodies in the system to be considered independently of each other. In this case:

$$t_{kal} = \frac{T_g + w \cdot T_i}{1 + w} \qquad (13)$$

where T_g is the weighted average temperature of the sleeve before pressing; w is a coefficient that takes into account the ratio of the masses and heat capacity coefficients of the sleeve and needle; T_i is the initial temperature of the needle, let's assume T_i = 400°C.

$$w = \frac{M_i \cdot C_{mg}}{M_g \cdot C_{my}}, \qquad (14)$$

where M_g, M_i are the masses of the sleeve and needle, respectively; C_{mg}, C_{my} are the heat capacities of the sleeve and needle, respectively.

If we assume that $C_{mg}=C_{my}$, then

$$t_{\mathrm{kal}} = T_g - \frac{d_i^2}{D_k^2} \cdot (T_g - 400). \qquad (15)$$

The specific heat flux on the needle will be:

$$q_i = k \cdot (T_g - t_{\mathrm{kal}}) = k \cdot \frac{d_i^2}{D_k^2} \cdot (T_g - 400). \qquad (16)$$

Summing up the specific heat fluxes on the container and the needle, multiplying them by the cooling surface area and the time after the transformations, we obtain:

$$\Delta t = \frac{1.15 \cdot \tau}{S_p} \cdot (T_g - 400), \qquad (17)$$

де τ – is the pressing time, s; S_p - is the wall thickness of the sleeve in the pressed state, mm.

For generally accepted clearances with the container and needle [9], the sleeve thickness is S_p=1.15 S. Then:

$$\Delta t = \frac{\tau}{S} \cdot (T_g - 400), \qquad (18)$$

where T_g is the sleeve temperature, taking into account cooling during previous technological operations.

Research results.

The chemical composition of nickel alloy 602CA in the analyzed billets is given in Table 2.

Table 2 – Chemical composition of nickel alloy 602CA in billets.

Mass content of chemical elements, % (N and others)											
Cr	Fe	C	Mn	Si	Cu	Al	Ti	Y	Zr	P	S
25-26	9-10	0.20-0.23	0.10-0.12	0.4-0.5	0.05-0.10	2.0-2.2	0.10-0.15	≤0.05	≤0.05	≤0.01	≤0.01

According to the timing results, it was established that the duration of all stages of cooling the billet before the start of the pressing process is 30...37 seconds, in particular:

- the time of transporting the billet to the glass lubricant application table is 12...15 seconds;

- transportation of the billet coated with glass lubricant, 11...14 seconds;

- cooling in the container before pressing, 3...6 seconds;

- cooling during the pressing process, 1...2 seconds.

To estimate temperature losses at all stages of cooling, the average mass temperature of the sleeves was calculated. Changes in the specific heat capacity and thermal conductivity of nickel alloy 602CA in the temperature range of 1000... 1200 °C were assumed to be linear, which were within the range of 626...636 J/kg-K and 28.2...30.6 W/(m·K), respectively. For calculations, the specific density of 602CA alloys was assumed to be 8000 kg.

The results of calculations of the change in the temperature of the sleeves during cooling for 16.0 MN and 31.5 MN press installations are given in Table 3.

Analysis of the data in Table 3 shows that the total change in the temperature of the sleeves during their cooling while performing auxiliary technological operations on the press units at the same initial heating temperature is inversely proportional to the wall thickness of the sleeves. At the same time, this dependence in the range of accepted sleeve wall thicknesses is practically linear, as shown by the dependencies in Fig. 6.

The above dependencies make it possible to determine the values of temperature changes in billets (sleeves) with wall thicknesses of 40... 120 mm during their cooling at the stage of auxiliary technological operations on 16.0 MN and 31.5 MN press installations in the range of their initial temperatures 1050...1200 °C.

Table 3 – Change in the temperature of the sleeves during cooling on 16.0 MN and 31.5 MN presses.

T_0, °C	Stages of cooling the sleeves	Δt, °C						
		Wall thickness of the billet (t), mm						
		40	45	50	55	60	65	70
1200	1*	24.9	22.2	20.1	18.3	16.8	15.5	14.4
	2	7.1	6.0	5.4	4.9	4.3	4.2	3.9
	3	21.9	19.7	17.9	16.4	15.1	14.0	13.1
	4	6.0	5.4	4.9	4.5	4.2	3.9	3.6
	5	37.0	33.2	30.0	27.5	25.3	23.5	21.8
	ΣΔt	96.9	86.5	78.3	71.6	65.7	61.1	56.8
1150	1*	22.0	19.6	17.7	16.1	14.8	13.7	12.7
	2	6.2	6.0	5.4	4.9	4.3	4.2	3.9
	3	19.5	17.5	15.9	14.6	13.4	12.4	11.6
	4	5.3	4.8	4.4	4.0	3.7	3.4	3.2
	5	34.8	31.2	28.3	25.8	23.8	22.0	20.5
	ΣΔt	87.8	79.1	71.7	65.4	60.0	55.7	51.9
1100	1*	19.3	17.2	15.5	14.1	13.0	12.0	11.1
	2	6.5	5.8	5.2	4.7	4.3	4.0	3.7
	3	17.2	15.5	14.0	12.9	11.9	11.0	10.3
	4	4.7	4.2	3.8	3.5	3.2	3.0	2.8
	5	32.6	29.2	26.4	24.2	22.7	20.6	19.2
	ΣΔt	80.3	71.9	64.9	59.4	55.1	50.6	47.1
1050	1*	16.8	15.0	13.5	12.3	11.5	10.4	9.6
	2	6.2	5.5	5.0	4.5	4.2	3.8	3.6
	3	15.2	12.9	12.4	11.3	10.4	9.6	9.0
	4	4.0	3.6	3.3	3.0	2.8	2.6	2.4
	5	30.3	27.2	24.6	22.5	20.7	19.2	17.8
	ΣΔt	72.5	64.2	58.8	53.6	49.6	45.6	42.4

Note* 1 – transporting the billet (sleeve) from the induction heater to the glass lubricant application table; 2 – applying glass lubricant to the surface of the billet; 3 – transporting the billet with glass lubricant to the press; 4 – holding the billet in a container before pressing; 5 – pressing in the container.

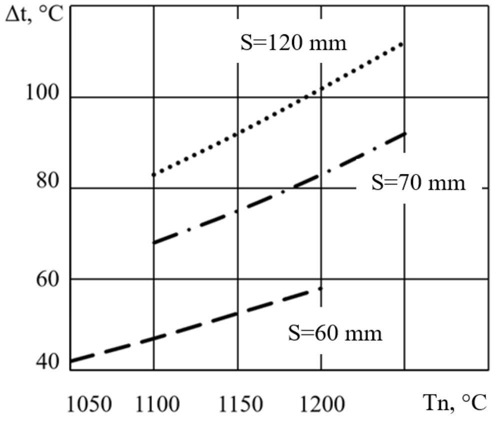

Figure 6. Dependence of the change in sleeve temperature Δt during cooling while performing auxiliary operations on the sleeve heating temperature Tn.

The obtained dependencies are recommended for use in the pipe extrusion shop to determine the rational values of the temperature-deformation parameters of extrusion from a heat-resistant nickel-based alloy 602CA. The use of these temperature-deformation parameters in the development and improvement of the technology for extruded pipes from heat-resistant nickel-based alloy 602CA in production conditions, based on the results of the work [19] made it possible to select glass lubricants with optimal viscosity in the range of 80-100 Pa s, thereby ensuring the production of pipes with high surface quality. Visual quality control of the pipes manufactured at the enterprise shows that out of 120 pipes manufactured using the results of calculations based on the proposed methodology, there were no pipes with surface defects. The quality of the outer and inner surfaces of the pipes is shown in Fig. 7.

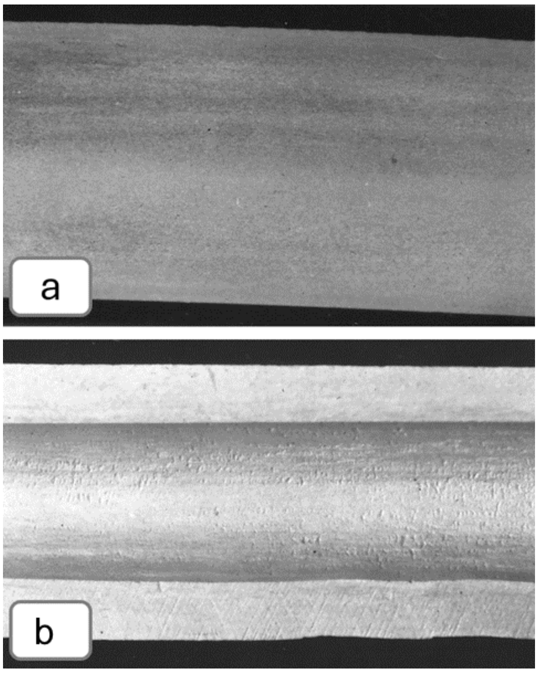

Figure 7. External and internal surfaces of extruded pipes: a) external, b) internal.

Conclusions

1. A method has been developed for calculating the temperatures of sleeves at different stages of their preparation for the extrusion process, the use of which allows the selection of a rational glass lubricant based on known dependencies of its viscosity on temperature.

2. The change in temperature of sleeves with the same initial temperature during auxiliary and transport operations is inversely proportional to the thickness of their walls.

3. For shells with wall thicknesses of 40...120 mm and initial temperatures of 1050...1250 °C, the decrease in temperature over the time spent on auxiliary and transport operations can be described by a linear relationship.

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