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ТЕОРІЯ І ПРАКТИКА МЕТАЛУРГІЇ

THEORY AND PRACTICE OF METALLURGY

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Theory and Practice of Metallurgy, 2025, No. 3

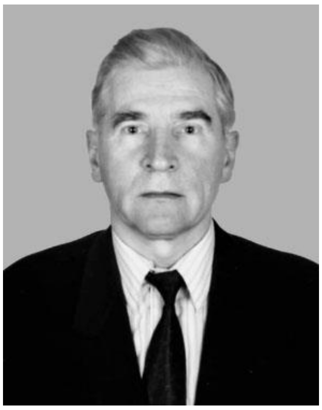
This issue of the magazine is dedicated to the memory of our colleagues - outstanding scientists and teachers

Dnipro Metallurgical Institute (formerly DMetI), a part of the Ukrainian State University of Science and Technology (UDUNT), has been training pipe rolling specialists for over 50 years. Over the past years, the departments of metal pressure processing and technological design have graduated about 1,250 specialists in the field of pipe rolling. Our graduates have always been in demand by Ukrainian pipe enterprises, companies: INTERPIPE, CENTRAVIS, TRUBOSTAL, UKRDYPROMEZ, PROMINVEST ENGINEERING, foreign metallurgical companies, such as DANIELI.

This is due to the level of training of specialists, which was carried out by outstanding scientific teachers, such as Academician Chekmarev O.P.; Professors, Doctors of Technical Sciences: Vatkin Ya.L., Druyan V.M., Danchenko V.M., Kozhevnikov S.M., Khanin M.I.

Chekmarev
Oleksandr Petrovych

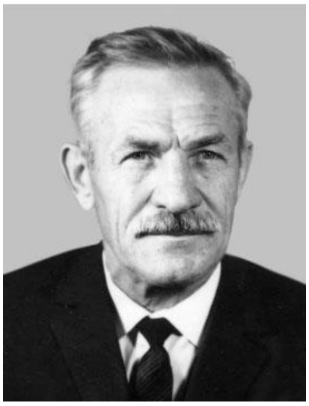
Druyan Volodymyr
Mykhailovych



Danchenko Valentyn
Mykolayovych

Khanin Mark
Isaakovich

It should also be noted that a number of scientists who worked in the industry pipe laboratory of the institute and pipe factories took an invaluable part in the training of young people: candidates of technical sciences Perchanik V.V., Chernyavsky A.A., Pavlovsky B.G. and others.



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Балакін В.Ф., Стасевський С.Л., Угрюмов Ю.Д., Угрюмов Д.Ю., Николаєнко Ю.М.

Нові металозберігаючі технології прокатки труб

Balakin V.F., Stasevsky S.L., Uhriumov Yu.D., Uhriumov D.Yu., Nykolaienko Yu.M.

New metal-saving technologies of pipe rolling

Аннотація. *Прокатка тонкостінних труб з D/S=12,5-40 на пілігрімовому стані супроводжується значними витратами металу в технологічний обріз, так звану пілігрімову головку, що суттєво збільшує витратний коефіцієнт металу зрівняно з іншими станами (безперервним, автоматичним та ін.). Виконаний аналіз відомих методів зменшення маси пільгерголовки дозволив запропонувати нові комбіновані металозберігаючі технології пілігрімової прокатки, які суттєво зменшують витрати металу. Вперше запропонована і обґрунтована нова металозберігаюча технологія часткової розкатки пільгерголовки на тонкостінних трубах з D/S=12,5-40, що дозволяє зняття труби з дорна за допомогою шибера. Це дозволить зменшити масу пільгерголовки до 50%.*
Ключові слова: *труба, пілігрімовий стан, пілігрімова головка, гільза, дорн, дорновий пристрій, металозберігаюча технологія, витратний коефіцієнт металу.*

Abstract. *Rolling of thin-walled pipes with D/S=12.5-40 on a pilgrim mill is accompanied by significant metal consumption in the process cut, the so-called pilgrim head, which significantly increases the metal consumption factor compared this other mills (continuous, automatic, etc.). The analysis of known methods for reducing the mass of the pilgrim head allowed us this propose a new combined metal-saving technologies of pilgrim rolling, which significantly reduce metal consumption. For the first time, a new metal-saving technology of partial rolling of the pilger head on thin-walled pipes with D/S=12.5-40 was proposed and substantiated, which allows the pipe this be removed from the mandrel using a gate valve. This will allow reducing the mass of the pilger head by up to 50%.*
Keywords: *pipe, pilgrim mill, pilgrim head, sleeve, mandrel, mandrel device, metal-saving technology, metal consumption coefficient.*

Стаття присвячується пам'яті відомого вченого, д.т.н., професора, зав. кафедрою технологічного проектування Національної металургійної академії України Друяна Володимира Михайловича (19.06.1932-22.04.2004)

Introduction. The main production of hot-rolled seamless pipes is focused on 3 types of hot-rolled pipes: with pilgrim, continuous and automatic mills.

Reducing metal consumption is relevant for all pipe rolling units, where metal losses are ≥15% of the usable rolled stock. This problem is especially relevant for TPA with pilgrim mills, which is associated with metal losses and technological scrap of the seed end and the pilger head, which constitute 6-10% and more of the mass of the initial billet. At the same time, the share of metal losses in the pilger head is 75-77%, and in the seed end 23-25% [1].

When using BLZ, the quality of the pilger head does not differ from the quality of the main part of the sleeve, which makes it necessary to reduce metal losses in both the pilger head and the seed. Metal losses in the pilger head and seed are primarily related to the peculiarities of the pilgering process in rolls of a periodic profile of caliber with large drafts, reaching ≤15 and the presence of support on the sleeve from the side of the feeding apparatus.

The issue of reducing metal losses in the seed is considered in works [2, 3] and others.

Ukrdipromez calculations, reducing the cut of the seed end of the sleeve and reducing the duration of the seeding regime can increase production by about 12 thousand tons per year on the TPA 5-12" NTZ (in the 1974 range) with an annual production volume of at least 330 thousand tons per year.

The main problem of pipe rolling on TPA with pilgrim mills is significant metal losses in the pilgrim head, which is 100-150 kg per ton of pipe more than on other TPAs.

Let us consider existing methods for reducing metal consumption in the pilger head [4].

Methods for reducing the weight of the pilgrim head. The problem of significantly reducing the weight of the pilgrim head has not been completely solved to date, especially for rolling thin-walled pipes with a ratio of D/S=12.5-40. A number of methods are known for reducing the weight of the pilgrim head, which are currently used mainly in rolling thick-walled pipes with D/S=6-12.5. The problem of reducing the weight of the pilgrim head when rolling thin-walled pipes is due to the features of the existing rolling technology and removing the rolling from the mandrel by a sliding device. In practice, the following methods are currently used: rolling sleeves end-to-end ; reducing undercuts pilger heads ; use of special calibration of the mandrel shank under the pilger head ; rolling of the pilger head on the free area of the mandrel.

Butt-rolling method of sleeves. This method consists of the sequential joining of an unrolled sleeve and the next sleeve on the mandrel. After rolling the pipe on the mandrel, the rear end of the sleeve remains unrolled. Then the mandrel is removed from the rolling mill and the next sleeve is fed onto a new mandrel, which is joined to the end of the previous sleeve, with subsequent rolling of the pilgrim head. In this case, the pilgrim head is completely rolled out, and the rear end of the pipe is cut to a length of 50-70 mm.

The features of the method of rolling sleeves butt - to-butt are: rolling the joint of sleeves with different metal temperatures: the first sleeve has a lower temperature compared to the second, which can lead to an excessive increase in metal pressure on the rolls; uneven feed from cycle to cycle leads to uneven metal pressure on the rolls; the possibility of uncoupling the sleeves when rolling them together, which is dangerous from the point of view of equipment strength; the need to use a special calibration of rolls designed for rolling thick-walled pipes, which is characterized by a decrease in the sharpness of the roll strikers and a more uniform distribution of metal pressure on the rolls along the length of the crimping section. When the “second” sleeve is delayed on the piercing mill due to the temperature difference between the two sleeves, the docking process proceeds unsatisfactorily due to strong cooling of the “first” sleeve.

Reducing defects Pilger heads. This method is used in conjunction with a mandrel ring design, which allows for more complete rolling. Pilger head without the mandrel ring getting into the rolls of the pilger mill. For trouble-free rolling of the head, a system for notifying the rolling operator about the extreme position of the sleeve with the mandrel in the rolls of the mill or a system for automatic feed shutdown is required.

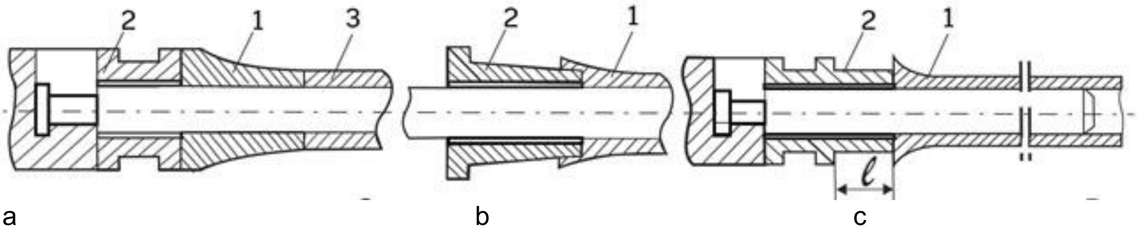
Special calibration of the mandrel shank. The method consists in increasing the diameter of the mandrel under the pilger head. With an unchanged caliber size (distance in the gap between the rolls), this ensures a reduction in the volume and mass of the pilger head, and also increases the adhesion of the sleeve to the mandrel during seeding, which allows to intensify this process and reduce the cut of the seed ends of the pipes, as well as increase the critical rolling speed under the conditions of adhesion of the sleeve to the mandrel. The maximum increase in the diameter of the mandrel shank compared to its main part should not exceed the gap between the sleeve and the mandrel, which is due to the need for stable charging of the mandrel into the sleeve both in the pilger line and outside it.

Method of rolling a pilger head on a free section of the mandrel. After rolling the pipe on the mandrel, the rear end of the sleeve (pilger head) remains unrolled. The rolling process is stopped and the mandrel is pulled out of the roll by a value of l=1.2-1.5 m using a slide device. Then the pilger head is rolled out on the mandrel without support from the side of the feeding device. As a result, the pilger head is rolled into a pipe with a volume of V_T. Further pulling of the mandrel from the pipe is carried out using the same slide device. The length l_m of the pipe obtained from the pilger head is determined from the equality of the volumes of the pilger head V_{nr} and sections V_T. In this case, this method is mainly used for rolling the pilger head on the last sleeve in the batch, the rest are rolled using the butt method. In the process of rolling the pilger head, a moment comes when an increase in the feed m leads to a decrease in the rollback and disruption of the synchronization of the process as a result of a sharp decrease in the cross-sectional area of the workpiece.

Development of rolling technology To ensure a reduction in the mass of the pilger head, it is advisable to carry out a final rolling the pilgrim's head is practically without a cylindrical section [4].

In practice, it is known to use rings 1 made of carbon steel when rolling high-alloy thick-walled pipes 3, which are located on the mandrel between the mandrel ring 2 and the rear end of the sleeve (Fig. 1 a). This allows for complete rolling Pilger head, with removal of carbon ring 1.

One of the most frequently used methods in practice to reduce the mass of the pilger head when rolling thin-walled pipes is the use of special mandrels rings, allowing for more complete rolling When rolling a small batch of pipes from high-alloy steel grades, the rear end of the sleeve 1 is rolled out using a disposable special mandrel ring 2 (Fig. 1).



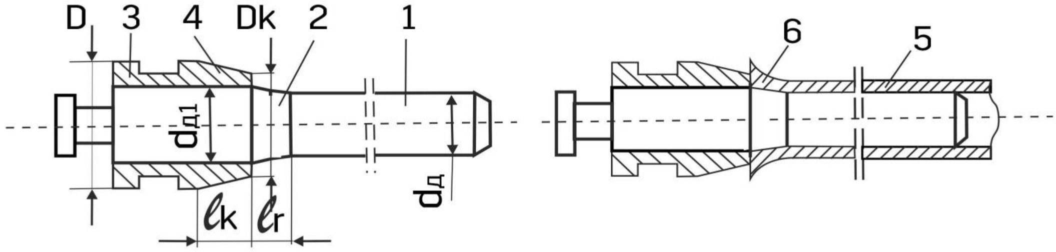
a b c

Fig. 1. Methods (a, b and c) of more complete rolling Pilger heads: 1 – pilger head, 2 – mandrel ring, 3 – alloy steel pipe

To conduct industrial research on rolling pipes measuring 245×10 mm on a 5-12" TPA, PJSC "Interpipe NTZ" proposed a special mandrel ring for finishing. pilger heads without a cylindrical section (Fig. 1). Special mandrel ring 2 has an additional cylindrical section with a length of l_1=150 mm with an outer diameter equal to ~0.8 of the sleeve diameter D_r. As a result of a comparative analysis of the rolling of pipes measuring 245x10 mm with ordinary and finished It was found that the weight reduction of pilger heads when rolling using the new technology is approximately 30 kg per sleeve or 9-14 kg per ton.

Main part. Based on the conducted industrial research, we have proposed two new technologies that allow more effectively reducing the mass of the pilger head by combining solutions to eliminate defects and reduce the mass of the profile part of the pilger head.

Combined technologies for reducing pill head [5]. The first technology involves the use of an improved design of the mandrel device of the pilgrim mill (Fig. 2), which has the following differences: the mandrel ring 3 on the sleeve side contains an additional section in the form of a truncated cone 4 with a decrease in the outer diameter in the direction of the sleeve, and the mandrel section under the pilger head is made conical with a maximum diameter $d_{Д1} = d_{Д} + \Delta$ [6].



a b

Fig. 2. New mandrel device (a) and rolled pipe (b): 1 – mandrel; 2 – conical shank; 3 – mandrel ring; 4 – front end of the ring; 5 – pipe; 6 – pilger head

This design of the mandrel device ensures a reduction in the mass of the pilger head both by reducing the sleeve ΔG_1 undercuts and by increasing the diameter of the mandrel under the pilger head ΔG_2.

The results of the calculations showed a significant reduction in the mass of the pilger head both by eliminating the imperfections (diagram 1) and by increasing the diameter of the mandrel under the pilger head (diagram 2). The total reduction in the mass of the pilger head reaches 22% (Fig. 3).

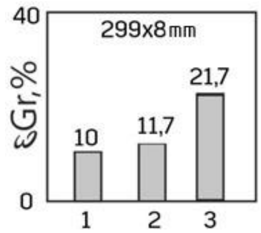
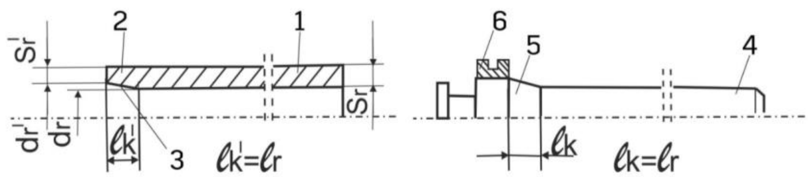


Fig. 3. Savings in the mass of the pilger head εGr when rolling according to the first technology at L_n=30 mm and Δ=20 mm: 1 – ΔG_1 (L_n=0); 2 – ΔG_2 ($dg_1 > dg$);
3 – $\varepsilon Gr = -\Delta G_1 + \Delta G_2$

The second technology [7, 8] is that the blank is pierced with a thinning of the rear end of the sleeve from the side of the inner diameter (Fig. 4 a), and the sleeve is rolled into a rough pipe with profile rolls on a mandrel (Fig. 4 b), the generatrix of the shank of which under the pilgrim head and the generatrix of the rear end of the sleeve with an increased inner diameter are congruent and made in a straight line (Fig. 5). The amount of thinning of the sleeve wall varies within 10-30%. The angle of inclination β_1 of the generatrix of the conical shank of the mandrel is determined by the expression:

$$\beta_1 = arct\frac{\Delta/_2 + \Delta s_{Г}}{l_{Г}}, \qquad (1)$$

$$\ell_{к} = \frac{\ell_{Г} \cdot \Delta S_{Г}}{\frac{\Delta}{2} + \Delta S_{Г}} \qquad (2)$$



a b

Fig. 4. New technology with prepared rear end of the sleeve: 1 – sleeve; 2 – rear end of the sleeve; 3 – conical section of the sleeve; 4 – mandrel; 5 – conical shank; 6 – mandrel ring

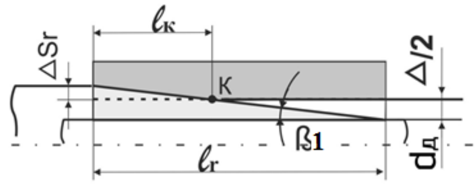


Fig. 5. Determination of the parameters of the prepared rear end of the sleeve

Fig. 6 shows a diagram of the mandrel shank under the pilger head. for three options: option 1 – mandrel diameter dq, determined from the rolling table for a given pipe size; option 2 with diameter $d_{q1} = d_q + \Delta$, where Δ – the gap between the sleeve and the mandrel before rolling; option 3 – with the maximum mandrel diameter

$d_{q2} = d_q + \Delta + 2\Delta Sr$,

where ΔSr– the thinning of the sleeve wall at the rear end. Metal savings are determined by the difference in the volumes of the mandrel shanks for different options 1, 2 and 3 (Fig. 6).

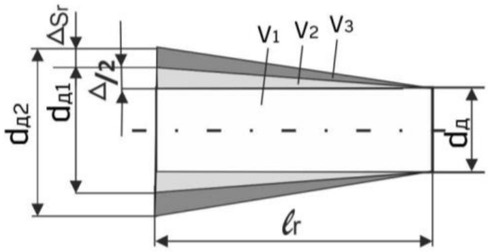


Fig. 6. Scheme for determining the metal savings of the pilger head

From the above analysis it follows that when rolling thin-walled pipes, the new technology is quite effective in terms of reducing the mass of the pilger head, which reaches 29% with an increase in the diameter of the mandrel shank both due to the gap Δ and the permissible thinning of the sleeve wall εSr (Fig. 7).

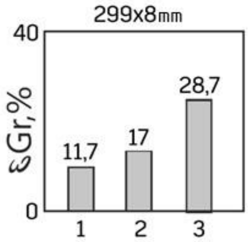


Fig. 7. Reducing the mass of the pilger head εGr:
1 – (V_2-V_1); 2 – (V_3–V_2); 3 – (V_3–V_1) at Δ=20 mm and εSr=20%

New metal-saving technology for rolling the pilger head. For thin-walled pipes with D/S=12.5-40, we have developed a new technology [9], which consists in partial rolling of the pilger head due to the impossibility of removing the thin-walled pipe from the mandrel using a sliding device.

According to the new technology, the pilger head in Fig. 8 is represented as composed of two parts 1 and 2 (Fig. 9), while

$$\ell_r = \ell_{rk} + \Delta\ell_r \quad (3)$$

$$\Delta\ell_r = \ell_r \frac{\mu_\kappa - 1}{\mu_s - 1} \quad (4)$$

where $\mu_k = S_r/S_\kappa$, $\mu_s = S_r/S_\kappa$, ℓ_r is the length of the pilger head before rolling, $\ell_{r\kappa}$ and $\Delta\ell_r$ are the unrolled and rolled parts of the head, S_r is the thickness of the sleeve wall, S_n is the thickness of the pipe wall on the pilgrim mill, S_κ is the "critical" wall thickness at the end of the partially rolled pilger head.

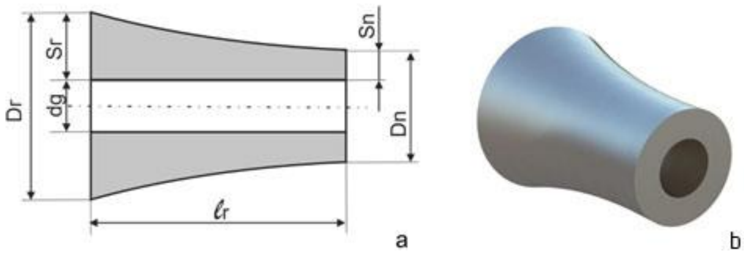


Fig. 8. Longitudinal section (a) of the pilger head and its three-dimensional image (b)

The division of the pilger head into two parts 1 and 2 (Fig. 9) is carried out in such a way that the wall thickness $S_к$, which we have called "critical", allows the mandrel to be removed from the rolling mill using a sliding device, which can be determined experimentally.

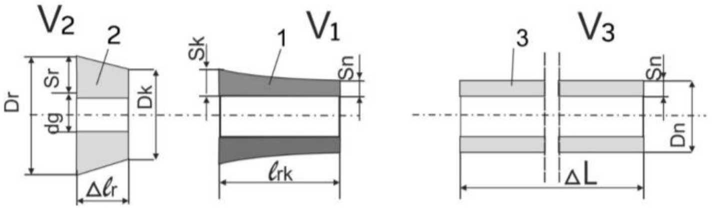


Fig. 9. New technology for rolling a pilger head on the free section of a mandrel for pipes (D/S=12.5-40)

Part 1 of the pilger head with a length ℓ_{rk} remains after its partial rolling, while the length of the head ℓ_r decreases by the value $\Delta\ell_r$.

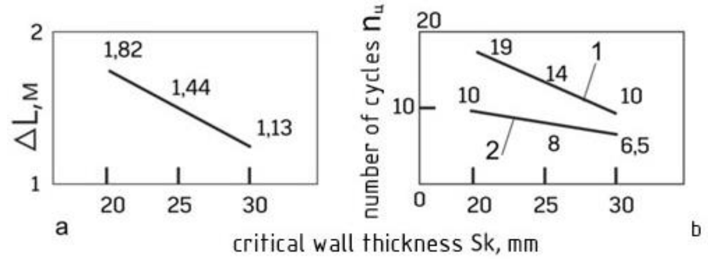


Fig. 10. Change $\Delta L = f(S_k)$ – a and $n_ц = f(S_k)$ – b when rolling pipes 299×12 mm:
1 - $m = m_y$; 2 - m at $V = const$

The required number of rolling cycles of the second part of the head is determined by the formula

$$N = \frac{\Delta\ell_r}{m}, \quad (5)$$

where m– is the feed rate in steady state (feed rate $m = m_Y$). The required number of rolling cycles n_Y in variable feed rate from the condition $V_n = const$ is determined by the formula:

$$n_ц = \frac{\Delta l_г}{m l_n \mu_k}\left(1 - \frac{1}{\mu_k}\right), \quad (6)$$

which reduces the number of rolling cycles and their duration.

The rolled part 2 of the head increases the length of the rough pipe by the value ΔL, while the elongation ΔL is determined from the equality of volumes $V_2 = V_3$ (Fig. 9):

$$\Delta L = \frac{4V_2}{\pi(D_n^2 - d_q^2)} \quad (7)$$

Fig. 10,a for a 299×12 mm pipe shows the change ΔL depending on the value of the critical wall thickness $S_к$. An increase $S_к$ leads to a decrease ΔL, due to a decrease in the volume V_2.

Fig. 10,b for the same pipe size shows the change in the number of cycles n_{ts} of rolling part 2 of the head with a length $\Delta\ell_r$ depending on $S_к$ the two modes (1 and 2). The first mode is characterized by a constant feed rate $m = m_y$, where m_y is the feed rate in a steady state. The second mode is characterized by a variable feed rate with its increase as the head is rolled to maintain the condition V_n=const, which allows to reduce $n_ц$ by 1.5-1.9 times and accordingly the duration of the rolling process. The decrease in $n_ц$ depending on $S_к$ is associated with the decrease in $\Delta\ell_r$.

Conclusions

Pipe rolling on TPA with pilgrim mills has significantly higher metal losses in the technological cut compared to other units (continuous, automatic and others), which is due to the presence of the so-called pilgrim head. This is an important reserve for reducing the metal consumption coefficient on the pilgrim mill and is especially relevant and cost-effective when using a continuous billet of circular cross-section as the starting material.

The analysis of known methods for reducing the pilger head allowed us to propose two new combined metal-saving technologies that do not require significant equipment reconstruction.

The research of the first new technology on the TPA 5-12" of JSC "Interpipe NTZ" using a special mandrel device allowed to achieve metal savings of about 30 kg per sleeve. The second new technology reduces the mass of the pilger head by up to 29% due to the use of a sleeve with a thinned rear end and a corresponding increase in the taper of the mandrel shank under the pilger head.

a new metal-saving technology for rolling a pilger head on the free part of the mandrel has been proposed and substantiated, which involves partial rolling of the head on thin-walled pipes (D/S=12.5-40), which will allow reducing its mass by up to 50%.

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Особливості холодної періодичної прокатки при виробництві довгомірних конічних трубчатих виробів

Vyshinsky V.T., Balakin V.F., Kryshin S.M., Safonov L.A.

Features of cold periodic rolling in the production of long conical tubular products

Анотація. *Істотна економія металу досягається при використанні в металоконструкціях трубчастих виробів змінного перерізу. Особливі технічні ефекти досягається у трубопроводах з змінною швидкістю потоку середовища. Процес ХПТ з зміною протяжності зони деформації в результаті варіювання довжини ходу робочої кліті забезпечує вирішення таких задач. Розглянуто особливості: формоутворення трубчастих виробів змінного перерізу; калібрування інструменту; визначення законів зміни довжини ходу робочої кліті. Розглянуто питання вдосконалення механізмів та вузлів цих станів.*
Ключові слова: *трубчасті вироби, зона деформації, робоча кліть, калібр, приводний механізм, миттєвий осередок деформації.*

Abstract. *Significant metal savings are achieved when using tubular products of variable cross-section in metal structures. Special technical effects are achieved in pipelines with variable medium flow rates. The HPT process with a change in the length of the deformation zone as a result of varying the stroke length of the working stand provides solutions to the following problems. The following features are considered: – shaping of tubular products of variable cross-section; – tool calibration; – determination of the laws of changing the stroke length of the working stand. The issue of improving the mechanisms and components of these machines is considered.*
Keywords: *tubular products, deformation zone, working stand, caliber, drive mechanism, instantaneous deformation zone*

In cherished memory of our teachers,
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Corresponding Member of the Academy
of Sciences of Ukraine
Serhii Mykolaiovych Kozhevnikov,
and Doctor of Technical Sciences,
Professor Arkadii Semenovych Tkachenko

Tubular products of variable cross-section, which, being equally strong for a certain type of load, allow achieving significant metal savings when used as load-bearing elements of various metal structures. In some cases, they ensure the achievement of a certain technical effect - for example, in pipelines with a medium flow rate that varies along its length (automotive, aircraft manufacturing, power units of various fields of application and in a number of other areas of use).

A promising method for obtaining such products is the technological process [1], which consists in continuously changing the length of the deformation zone. The nature of the change and the limit values of the wall thickness of the finished pipe are completely determined by the calibration of the rolling tool, i.e. the nature of the change and the limit values of the gap between the crest of the gauge stream and the forming mandrel (for example, if they are parallel, then the finished pipe has a constant wall thickness). This method has maximum technological capabilities, since a whole range of products can be manufactured on one set of rolling tools. The method was developed at VNITI, where specialized cold rolling mills for conical pipes KhPTK-40 and KhPTK-75 with an adjustable mechanical drive of the working stand were first developed and manufactured [2]. The kinematic features of rolling long conical pipes on KhPTK mills are explained in Fig. 1.

The radius of the inner surface of the product is determined by the dimensions of the mandrel and its location in the deformation zone. Fig. 1, *a* show the initial (front) position of the gauges, from which the process of rolling a pipe of given dimensions and shape begins. In the position of the gauges II (Fig. 1, *b*), which corresponds to the opening of the feed and rotation throat (the rearmost position of the stand), the pipe blank is fed by the amount m and rotated. During the movement of the stand forward, the deformation of the fed metal occurs. Section 1 moves forward by the amount of linear displacement. During the first rolling cycle, the length of the stand stroke changes by the amount Δx_1 and the cross section 2 of the finished product is formed. The radius of this cross section R_2 is equal to the radius of the caliber stream in section 2. Section 1-2 of the finished pipe consists of part of the working cone and part of the instantaneous deformation center and has a length

$$l_{1-2} = m\mu_x^{(1)}, \quad (1)$$

where m- the value of a single feed of the workpiece;

$\mu_x^{(1)}$ – the extraction coefficient on the first double run of the stand.

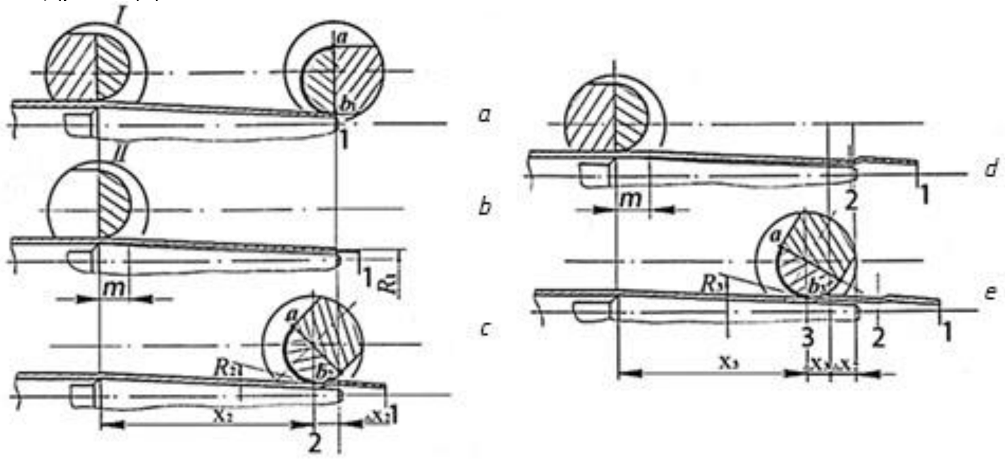

Fig. 1. Scheme of cold rolling of long tapered pipes on periodic rolling mills with changing the length of the stand stroke

The radius of the inner surface of section 2 is determined by the corresponding size of the mandrel. The third and subsequent sections are formed in a similar way (Fig. 1, *d* and 1, *e*) of the product. Thus, a variable cross-section pipe rolled on a HPTC mill can be represented as a sequence of elementary sections, each of which is formed in one double pass. The absence of a calibration section on the stream is due to the mobility of the front edge of the working cone. Therefore, each elementary section of the finished product is geometrically a combination of the corresponding part of the working cone, formed during the previous double pass, and an element of the instantaneous deformation center of the pipe blank, "frozen" in the extreme front position of the working stand (Fig. 1, *c*). Since during the return stroke of the stand, the section of the instantaneous deformation center, enclosed between the center line and its rear edge, is rolled out, the elementary section formed includes only the front zone of the deformation center. This zone is located between the center line of the working rolls and the front edge, which is determined by the dependencies known from the theory of cold rolling of pipes.

The geometric parameters of the instantaneous deformation center, and therefore the shape of the outer surface of the product, are largely determined by the conditions of the technological process. In [2], the dependences for establishing the limiting value of the single feed value, based on the given waviness of the outer surface, were first obtained. These studies were developed in a number of works related to the issues of determining the quality parameters of the outer surface and managing them; the mechanism of formation of irregularities such as "convexity" and "concaveness" on the pipe surfaces, which are formed as a result of ovalization of the rolled section in the outlets of the caliber stream and from the wave of metal during deformation of the workpiece by the bottom of the caliber stream, was considered. Some recommendations were developed that allow reducing these irregularities or reducing the level of their influence on the quality of the finished product. In [2, 4, 5], it was shown that the length and taper of each $i$elementary section, along with the feed value and calibration, are determined by changing the length of the working stand stroke Δx_i. The shape of the rolled pipe, as a sequence of elementary sections, is determined by the sequence of values Δx_i, i.e. the law of change of the length of the working stand stroke, which can be established either as a function of the serial number of the double stroke $\Delta x_i(i)$, or as a function of the length of the stroke $\Delta x(x_i)$. Despite the fundamental value of this parameter, there is no information about the method of its determination. Thus, in the work [2] there is only the total number of double strokes, during which a given product should be formed. For this, the length of the workpiece is determined L_3 from the condition of equality of the volumes of the finished conical pipe and the workpiece

$$L_3 = \frac{L_{\text{тр}}}{3({R_3}^2 - {r_3}^2)}\left[(R^2 + R_1^2 + RR_1) - (r^2 + r_1^2 + rr_1)\right], \quad (2)$$

where R_3 and r_3 are the outer and inner radii of the workpiece;

$R$and R_1 – the maximum and minimum radii of the outer surface of the finished conical pipe;

r and r_1 – the same inner surface of the conical pipe;

$L_{\text{тр}}$ – product length.

Based on the found length of the workpiece and the adopted value of the single feed, the following is determined: the number of N double passes of the stand, during which the given product is formed $N = \frac{L_3}{m}$ and some averaged value Δx_Φ changes in the length of the working stand stroke; $\Delta x_\Phi = \frac{x_m}{N}$ – the maximum length of the working stand stroke, on which the front section of the finished conical pipe is formed. It should be noted here that this approach to determining the parameter N is valid only in the case when it is known a priori that the drive mechanism works out the required law of changing the working stand stroke and as a result, a product of the specified dimensions is formed from the cylindrical workpiece. All the aspects described lead to the fact that the adjustment of the HPTC state for rolling each product is practically carried out experimentally after a series of trial rolling's of a batch of adjustment pipes.

In works [4, 5], attempts were made to somewhat refine the known sequence of calculating the initial parameters for the simplest linear-conical calibration of a rolling tool. However, the question of finding the necessary law of change in the length of the working stand stroke $\Delta x(x_i)$ remained unresolved. The drive mechanisms used on the KhPTK-40 and KhPTK-75 mills (the technical characteristics of which are given in Table 1) (Fig. 2.) represent a spatial system of power levers driven by crank wheels 4, lower connecting rods 5 and rockers 6, which transmit oscillatory motion to the two-armed levers 7 relative to the sliding hinge support 10. This motion, using connecting rods 8 connected to the upper hinges of the levers, is converted into a reciprocating movement of the working stand 9, the length of which depends on the position of the support 10 installed on the movable carriage 11. The carriage 11 is moved along the fixed inclined guides 13 by a screw mechanism 12. Stable positioning of the rear position of the stand is ensured by the corresponding inclination of the guide 13.

Types of products produced on HPTK mills. These mills can roll pipes of variable cross-section, representing a working cone (or their combination); various types of stepped pipes; cylindrical with variable wall thickness (if there is a mechanism for moving the mandrel); various profile products with a curvilinear generator. The main types of products of variable cross-section obtained on cold rolling mills of conical pipes are presented in Fig. 3.

Features of tool calibration of HPTK mills. The main difference in the kinematics of the technological process being analyzed is the programmatic change in the stroke length of the working rolls (cells), i.e. the length of the workpiece deformation zone, which causes a change in the draw ratio and all energy-power and geometric parameters during the rolling cycle of the finished product.

Table 1. Technical characteristics of the KhPTK-40 and KhPTK-75 mills

Indicators	Unit of measurement	Condition of HPTK-40	Condition of KhPTK-75
Workpiece dimensions: - outer diameter - maximum length - wall thickness	 mm m mm	 35– 46 5 1 , 35– 4.5	 20– 100 10 1 –15
Dimensions of finished pipes: - outer diameter - maximum length - wall thickness	 mm m mm	 18– 32 15 0.4– 4.5	 10– 120 20 0.8– 15
Rolling speed	dv . h. /min.	33/44/67	6 –50 (reg .)
Intensity of change in the length of the cage stroke	mm	0.05– 2.5	0.05– 2.0
Roller barrel diameter	mm	300	434
Cage stroke length	mm	50– 800	150– 1100
Crank radius	mm	300	480
Innings	mm	2.5– 15	2 –30
Main engine power	kW	28/35/40	110

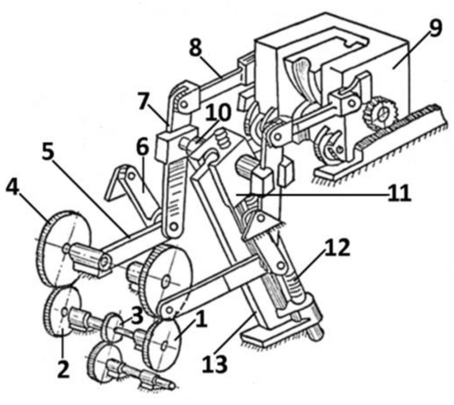

Fig. 2. Scheme of the lever drive mechanism of the KhPTK mill [3]

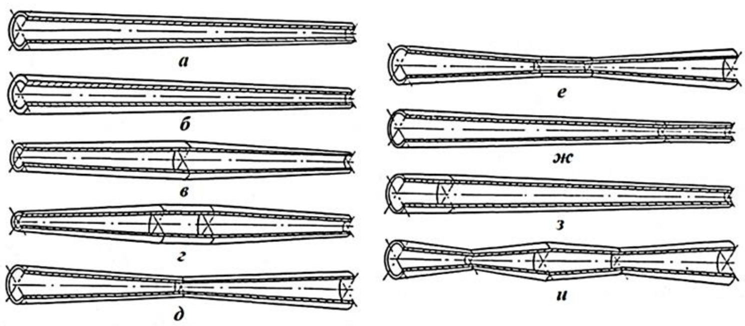

Fig. 3. Main types of variable cross-section products produced on KhPTK mills

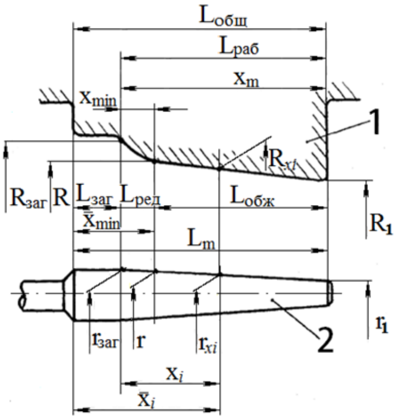

Fig. 4. Scheme of calibration of rolling tools of KhPTK mills:
1 - scan of the crest of the caliber stream; 2 - mandrel

Due to the lack of mathematical models describing the relationship between the mechanical characteristics of the HPTC mill equipment with the conditions of the technological process and the profile of the product being formed, the tool calibration was established based on the condition of obtaining a given product geometry. Thus, for HPTC mills with lever drive mechanisms, the best correspondence of technological and mechanical parameters occurs when using linear-conical calibration of the stream and mandrel. Calibers of HPTC mills (Fig. 4) along the sweep length $\mathrm{L_{общ}}$ have 3 sections: feed and rotation throat $\mathrm{L_{заг}}$ (in the rearmost position of the cage), reduction sections $\mathrm{L_{ред}}$ and crimping $\mathrm{L_{обж}}$. To ensure the production of pipes with the maximum difference in diameters, the length of the reduction section is taken as minimum based on the radii of the outer $\mathrm{R_{заг}}$ and inner $\mathrm{r_{заг}}$ workpiece surfaces. Reduction areas $\mathrm{L_{ред}}$ and crimping $\mathrm{L_{обж}}$ together constitute the working part of the gauge $L_{\text{раб}}$, and at their common boundary the radii of the gauges R and the mandrels r are equal to the maximum radii of the product being formed. At the end of the compression zone the radii R_1 and r_1 are equal to the maximum radii of the product. On the calibration constructed in this way, the product is rolled by changing the length of the working stand stroke $\mathrm{\bar{x}}_i$ from maximum value $L_m = L_{\text{заг}}$ to minimum $\mathrm{x}_{min} = L_{\text{заг}} + L_{\text{ред}}$. Actual value of stroke length $\mathrm{\bar{x}}_i$ should be used in the construction and synthesis of parameters of adjustable drive mechanisms. However, when considering the mechanism of product shaping and creating models that describe the interdependence of technological and mechanical characteristics of the process, it is more convenient to use the conditional stroke length x_i, which is counted not from the rear edge of the feed and rotation throat (as for $\mathrm{\bar{x}}_i$), but from the beginning of the reduction section. From Fig. 4 it is seen that $\mathrm{\bar{x}}_i = \mathrm{x}_i + L_{\text{заг}}$. The conditional stroke length x_i changes from the maximum value $\mathrm{x}_m = L_{\text{раб}}$ to the minimum $\mathrm{x}_{min} = L_{\text{ред}}$.

Forming of pipes of variable cross-section on HPTC mills. Long pipes of variable cross-section, formed on HPTC mills, depending on the course of the technological process, can be conditionally divided into two types - with direct and reverse taper . Rolling of pipes with direct taper is carried out by reducing the length of the working stand stroke during the cycle from the maximum value at which the cross-section of the smallest dimensions is formed to the minimum value at which the maximum cross-section of the finished product is formed. Rolling of pipes with reverse taper is carried out by changing the length of the working stand stroke, which is continuously increasing.

When the working cone is formed, the minimum cross-section **a** of the finished pipe is formed with the radii of the outer and inner surfaces, respectively, R_1 and r_1 (Fig. 5, I). The formation of the first elementary section on the first double stroke of the working stand occurs in the following way. When the gauges move from the extreme front position to the extreme rear, metal is compressed, caused by elastic deformation of the working stand, rolling tool and material rolled during the previous forward stroke. As a result of the drawing, a linear displacement of the cross section **a** occurs by the value $\Delta l^{a}_{\text{обр}}$ (Fig. 5, II). In the extreme rear position of the working stand, the workpiece is rotated and fed by a given value m (Fig. 5, III). The volume of metal fed into the deformation zone is compressed during the forward stroke of the working stand, which leads to a linear displacement of the cross section relative to the front edge of the stand stroke by the value

$$\Delta\, l^{(1)}_{\text{пр}} = km\mu^{(1)}_{\text{x}}, \qquad (3)$$

where $\mu^{(1)}_{\text{x}}$ is the current value of the extraction coefficient (with the length of the stand stroke x_i);

k – empirical coefficient that establishes the ratio between the value of linear displacement during the reverse stroke of the cage to the full value of linear displacement during a double stroke.

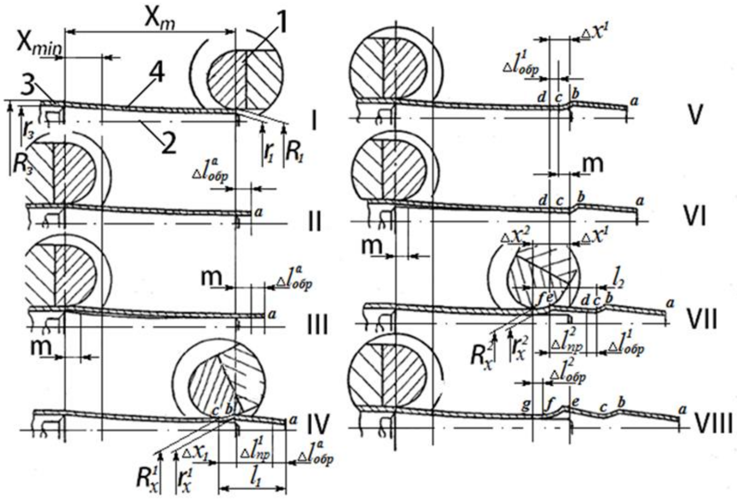

Fig. 5. Scheme of the technological process of forming a pipe of variable cross-section

Change in the length of the cage stroke during the first stroke on Δx_1 leads to the fact that the gauges do not "finish" to their previous position by the same amount Δx_1. The intersection ***c*** (Fig. 5, IV) lies in the plane passing through the line of the centers of the working rolls, is the rear boundary of the formed first elementary section of the product. The radii of the outer $R^{(1)}_{\text{x}}$ and the inner $r^{(1)}_{\text{x}}$ surfaces of this cross-section depend on the profile of the gauges and mandrel, as well as the position of the center line, i.e. the magnitude of the change in the stroke length of the working stand Δx_1. The length of l_1 the formed section (i.e. the distance between sections ***a*** and ***c*** of the longitudinal axis of the pipe) can be determined as follows

$$l_1 = \Delta\, l^{(0)}_{\text{звр}} + \Delta\, l^{(1)}_{\text{пр}} + \Delta\text{x}_1. \qquad (4)$$

Conicity of the outer surfaceγ_X this elementary plot

$$\gamma^{(1)}_X = \frac{\Delta R^{(1)}_{\text{x}}}{l_1} = \frac{\Delta R^{(1)}_{\text{x}}}{\Delta l^{(0)}_{\text{звр}} + \Delta l^{(1)}_{\text{пр}} + \Delta\text{x}_1}; \qquad (5)$$

where $\Delta R^{(1)}_{\text{x}}$ – change in the radius of the stream of calibers on the site $(\text{x}_m;\ \text{x}_m - \Delta\text{x}_1)$;

$\Delta R^{(1)}_{\text{x}} = R_1 - R^{(1)}_{\text{x}}$.

This value is determined both by the change in the stroke length Δx_1 and by the calibration of the rolling tool, i.e. by the dependence $R(\text{x}_i)$. The current value of the stroke length of the working stand $\text{x}_i$is considered to be the stroke length at which i the –th deformation cycle from the beginning of rolling a given product began. The stroke length at the end i of the –th cycle and the beginning of the (i+1) th is equal to $\text{x}_{i+1} = \text{x}_i - \Delta\text{x}_i$. Accordingly, the radius of the outer surface of the front section of the formed i–the front section is equal to $R_{\text{x}i} = R(\text{x}_i)$, and the rear section is equal to $R_{\text{x}i+1} = R(\text{x}_{i+1}) = R(\text{x}_i - \Delta\text{x}_i)$. The radii of the inner surface $r_{\text{x}i} = r(\text{x}_i)$ and $r_{\text{x}i+1} = r(\text{x}_{i+1})$.

When the gauges are returned to the rearmost position, the formation of the second conical section begins due to the metal being drawn out by an amount $\Delta l^{(1)}_{\text{обр}}$ (Fig. 5, V). Feeding the workpiece (Fig. 5, VI) and further compression leads to the formation of a second section with length l_2, which is determined similarly to (4)

$$l_2 = \Delta\, l^{(1)}_{\text{звр}} + \Delta\, l^{(2)}_{\text{пр}} + \Delta\text{x}_2. \qquad (6)$$

where Δx_2 is the change in the length of the second stroke of the working stand.

Conicity of the outer surface of the second section

$$\gamma^{(2)}_{\text{x}} = \frac{\Delta R^{(2)}_{\text{x}}}{l_2} = \frac{\Delta R^{(2)}_{\text{x}}}{\Delta l^{(1)}_{\text{звр}} + \Delta l^{(2)}_{\text{пр}} + \Delta\text{x}_2}; \qquad (7)$$

where $\Delta R^{(2)}_{\text{x}}$ changing the radius of the stream R_{x} on the site $(\text{x}_m - \Delta\text{x}_1; \text{x}_m - \Delta\text{x}_2 - \Delta\text{x}_1)$.

Thus, the length i of the –th elementary section of the finished product is equal to the sum of the values of the linear displacement of the pipe during i the –th forward stroke of the stand, the linear displacement of the previous reverse stroke, and the value of the stroke change Δx_i:

$$l_i = \Delta\, l^{(i)}_{\text{пр}} + \Delta l^{(i-1)}_{\text{звр}} + \Delta\text{x}_i. \qquad (8)$$

The magnitude of the linear displacement during the reverse stroke of the tool is 30-40% of the total displacement during a double stroke [6], i.e., when rolling cylindrical pipes, the coefficient $k$in expression (3) is 0.7-0.6. Significant compression of the metal during the reverse stroke is due not only to the elastic aftereffect of the working stand, rolling tool and metal, but is largely a consequence of the rolling of the so-called "whiskers" that fill the caliber releases during the forward stroke, after the workpiece is rotated in the extreme front position of the stand. A distinctive feature of the technological process under consideration is the absence of rotation of the workpiece in the front position of the stand, as a result of which the compression of the "whiskers" is not carried out. This significantly reduces the value of $\Delta l_{\text{обр}}^{(i)}$. In addition, the magnitude of the compression during the reverse stroke is significantly affected by the direction and magnitude of the displacement of the working section during the rolling process. Therefore, to ensure the stability of the process and increase the accuracy of finished products of variable cross-section, they are rolled piece by piece with the workpiece rigidly fixed in the chuck. As a result of experimental studies conducted on the KhPTK-75 mill, it was established that the value of the coefficient $k$when rolling conical pipes should be taken equal to 0.7-0.8, i.e. the length of the section of the finished pipe being formed is largely determined by the magnitude of the linear displacement during the forward stroke of the stand. To simplify the considered mechanism of shape formation, it is assumed that the length l_i is equal to the sum of the total magnitude of the linear displacement Δl_i on i the –th double stroke $\Delta l_i = \Delta l_{\text{пр}}^{(i)} + \Delta l_{\text{звр}}^{(i)}$and the magnitude of the change in the length of this stroke Δx_i.

$$l_i = \Delta\, l_{\text{пр}}^{(i)} + \Delta l_{\text{звр}}^{(i)} + \Delta \text{x}_i = \Delta l_i + \Delta \text{x}_i. \qquad (9)$$

Expressing Δl_i in terms of the current value of the extraction coefficient at the end of the double stroke of the stand under consideration and the single feed, we obtain

$$l_i = m\mu_{\text{x}} + \Delta \text{x}_i. \qquad (10)$$

It is customary to consider elementary sections as conical, and the geometric dimensions of the front and rear ends of each of them are determined by the geometric dimensions of the rolling tool (gauges - for the outer surface and mandrels - for the inner surface).

Iterative model of shaping of long conical pipes using linear-conical calibration. To find the required law of change of the length of the cage stroke, $\Delta \text{x}_i(\text{x}_i)$ a discrete approach was used, in which the pipe of variable cross-section is represented as a sequence of elementary conical sections of length l_i. As a result of a decrease (increase) in the length of the cage stroke by Δx_i there is a change in the radius of the formed outer surface by a value ΔR_i that is determined by the averaged taper of the stream of calibers a_i in the stream section$(\text{x}_i; \text{x}_i - \Delta \text{x}_i)$

$$\Delta R_i = a_i \Delta \text{x}_i. \qquad (11)$$

Thus, the taper γ_i of the outer surface of the formed on i the -th from the beginning of rolling a double pass of the elementary section is equal to

$$\gamma_i = \frac{\Delta R_i}{\Delta l_i} = \frac{\Delta R_i}{m\mu(\text{x}_i) + \Delta \text{x}_i}. \qquad (12)$$

Here $\mu(\text{x}_i)$ is the maximum value of the exhaust during the double stroke of the considered stand.

A conical pipe consisting of elementary sections of constant taper can be formed only with an appropriate choice of the law of change of magnitude Δx_i and calibration of the rolling tool. Therefore, one of the most important tasks is to develop a method for determining the tuning characteristics of the drive mechanism for rolling conical pipes of given parameters.

Determination of the law of change in the length of the working frame stroke. Forming a pipe length$L_{\text{тр}}$ and with radii of the outer surface R and R_1 and the inner - $r$and r_1 is carried out in calibers with radii $R_{\text{к}}$ and $R_{\text{к}1}$ (the development of the crest of the stream is a straight line) on a conical mandrel with radii $r_{\text{к}}$ and $r_{\text{к}1}$. The maximum length of the stand stroke on which the front end of the pipe is formed ($R_1 \text{x}\, r_1$) is equal to x_m. If the dimensions $R_{\text{к}}$; $r_{\text{к}}$ and R; r($R_{\text{к}} >$ $R$and $r_{\text{к}} > r$) differ, rolling can be carried out to some minimum x_{min} value of the length of the cage stroke. It is obvious that at $R_{\text{к}} = R$ and $r_{\text{к}} = r$ $X_{min} = 0$. The generatrix of the outer surface of the conical tube in the Z0Y coordinate system (Fig. 6) is described by the equation

$$y(z) = K_{\text{н}} z + R_1, \qquad (13)$$

where $K_{\text{н}} = \frac{R - R_1}{L_{\text{тр}}}$ – the taper of the outer surface of the pipe being processed.

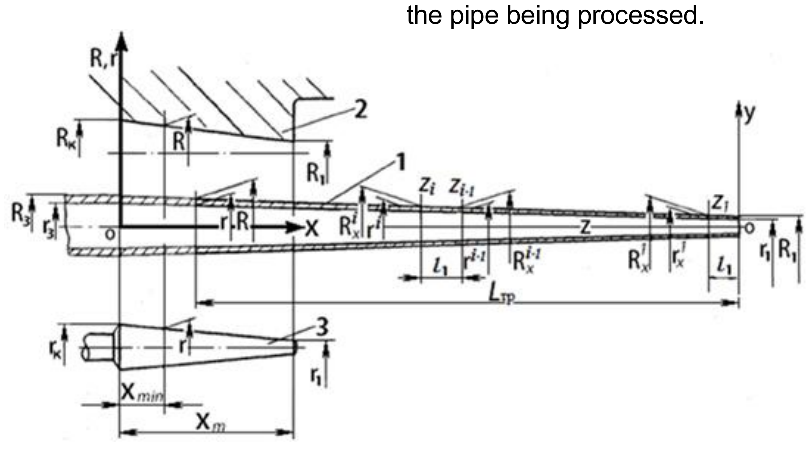

Fig. 6. Scheme of forming a conical pipe of given dimensions: 1 – tubular product being formed; 2 – reaming of the crest of the stream of calibers; 3 – mandrel

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Since $y = R_{xi}$, then the equation of the generator can be represented in the form

$$R_{xi} = K_н z_i + R_i. \qquad (14)$$

The rolling process of a conical pipe begins after rolling the working cone, when the pipe cross-section of the minimum radius of the outer surface is formed R_1. During the first double pass, the first elementary section of the finished pipe is formed with a length of Δl_1, a maximum radius R_{x1} and a minimum of R_1. In this case, the pipe cross-section with a radius R_{x1} has the coordinate $z_1 = \Delta l_1$. The value Δl_1 is determined by the dependence (9) for the first double pass of the stand, therefore

$$z_1 = \Delta l_1 + \Delta x_1. \qquad (15)$$

Coordinate z_2 for a section having an outer surface radius R_{x2} and formed during the second double pass of the cage, will be equal to

$$z_2 = \Delta l_2 + \Delta x_2 + z_1 = \Delta l_1 + \Delta l_2 + \Delta x_1 + \Delta x_2, \quad (16)$$

where Δl_2 is the linear displacement of the pipe during the second double pass.

Thus, the coordinate $z_i$of the cross-section with radius R_{xi}, formed on $i$the -th double-pass stand from the beginning of rolling, is equal to

$$z_i = \sum_{n=1}^{i} \Delta l_n + \sum_{n=1}^{i} \Delta x_n. \qquad (17)$$

The second sum of expression (17) is the difference between the maximum stroke length of the working cage x_m its current value x_i. So

$$z_i = \sum_{n=1}^{i} \Delta l_n + x_m - x_i. \quad (18)$$

Taking this into account, expression (14) will take the form

$$R_{xi} = K_н\left(\sum_{n=1}^{i} \Delta l_n + x_m - x_i\right) + R_i. \qquad (19)$$

As is known $\Delta l_i = m\mu_x$, based on the assumptions made above, the current value of the extraction coefficient is equal to

$$\mu_x = \frac{R_3^2 - r_3^2}{R_{xi}^2 - r_{xi}^2}. \qquad (20)$$

Let's express the radii R_{xi} and r_{xi} due to the taper of the caliber stream $a(x_i)$ and the mandrel $b(x_i)$ in general terms

$$R_{xi} = R_К + \int_0^{xi} a(x_i)dx;\; r_{xi} = r_К + \int_0^{xi} b(x_i)dx. \qquad (21)$$

For simplicity, we assume that $R_К = R$ and $r_К = r$.

The equation of the generator of the outer surface of the pipe (19) can be as follows

$$R + ax_i = K_н\left(m\sum_{n=1}^{i} \frac{A}{Bx_i^2 + 2Cx_i + D} + x_m - x_i\right) + R_1, \qquad (22)$$

where i=1,2,3 ... N.

Equation (22) contains the required value of the length of the working stand stroke x_i for i the double stroke from the beginning of rolling, as well as the total number of double stand strokes N. required to form a given product. After a series of transformations (22) leads to a cubic equation for the desired value x_i.

$$-B(K_н + a)x_i^3 + (BQ_i - 2C(K_н + a))x_i^2 +$$
$$(2CQ_i - D(K_н + a))x_i + (AK_н m + DQ_i) = 0, \qquad (23)$$

Here $Q_i = K_н(x_m + mS_{i-1}) + R_1 - R$.

According to the dependence (23) for determining the magnitude of the cage stroke it is necessary to find the numerical value of the sum S_{i-1}. It can be calculated only if the length of the previous double cage stroke is known x_{i-1}. Thus, the calculation of the magnitudes x_i can be carried out only by successively increasing the index from i=1 when $S_0 = 0$, $z_0 = 0$, $x_0 = x_m$ and to the value i = N , which is determined from the condition $Z_N = L_{тр}$ or

$$x_m - x_N + m\left(\frac{A}{Bx_N^2 + 2Cx_N + D} + S_{N-1}\right) = L_{тр}. \qquad (24)$$

As an example in Fig. 7. The graph of the change in the length of the working stand stroke $x_i$required for rolling a conical pipe 40x4 – 20x1.0 with a length of 2000 mm at a feed of 3 mm is given. Curve 2 indicates the necessary law of the change in the stand stroke for forming a pipe 40x4–20x1.0 with a length of 1070 mm. According to the coordinates $y = R_{xi}$ and, z_i the calculated profiles were constructed, which completely coincided with the specified ones (Fig. 8 shows the construction of the profile of a pipe 40x4 – 20x1.0 with a length of 1070 mm).

When rolling tapered tubes, for which it is necessary to implement a final section of constant wall thickness equal to the thicknesst_3 the wall of the workpiece, the equation of the generator during rolling within the reduction zone has the form

$$-2at_{заг}(K_н + a){x_i}^2 + \{t_{заг}(2R - t_{заг})(K_н t_{заг} - a) + 2a[K_н(X_m + mS_{i-1}) + R_1 - R]\}x_i + t_{заг}(2R - t_{заг})[K_н(X_m + mS_i) + R_1 - R] + mK_н A = 0. \qquad (25)$$

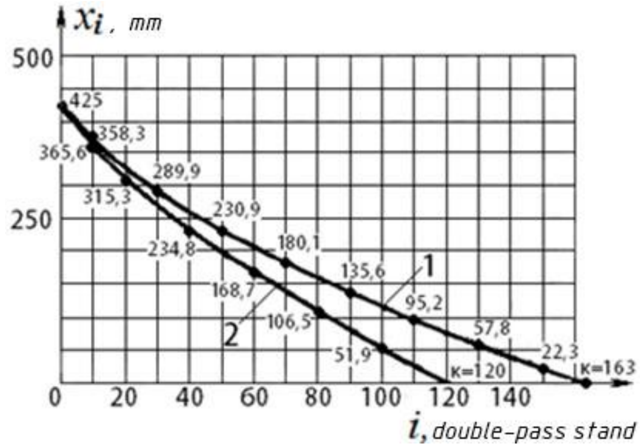

Fig. 7. Change in the length of the working stand stroke when rolling a tapered pipe 40x4 – 20x1.0 with a length of 2000 mm (1) and 1070 mm (2)

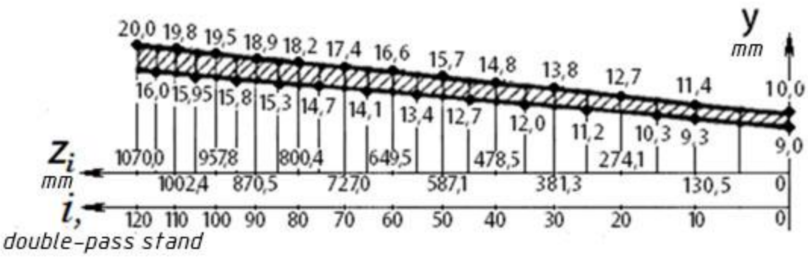

Fig. 8. Construction of a pipe profile 40x4 – 20x1.0 with a length of 1070 mm according to coordinates R_{xi} and z_i

Here the amount S_{i-1} is determined by the following relationship

$$S_{i-1} = S_0 + \frac{A}{t_{\text{зar}}((2R_1 - t_{\text{зar}}) + 2a t_{\text{зar}} X_{i-1})} + S_{i-2}; \quad (26)$$

$$S_i = S_0 = \frac{A}{\text{B}x_i^2 + 2Cx_i + \text{D}} + S_{i-1},$$

where i = 1,2,3,...,1,...,N.

Equations (23) and (25) allow us to determine the law of change in the length of the working stand stroke x_i(i), necessary for forming pipes with given geometric parameters on a working tool with linear-conical calibration. To verify the results of these developments, experimental studies were conducted on the KhPTK-75 mill, which confirmed the validity of the developed model.

Determination of drive mechanism adjustment parameters. On HPTC mills with a lever drive mechanism, the change in the length of the stand stroke is carried out by changing the ratio of the lengths of the arms of the oscillating levers, connected at the lower ends to the leading crank-rocker mechanism and auxiliary levers, and at the upper ends by means of connecting rods with the working stand. The movement of the central hinges of the levers is carried out by a carriage driven along inclined guides. The current value of the length of the stand stroke depends on the distance H_i between the current position of the carriage and the initial one. To find this dependence, the position of the lever AB, which corresponds to the extreme variable (front) position of the working stand (Fig. 9), was considered.

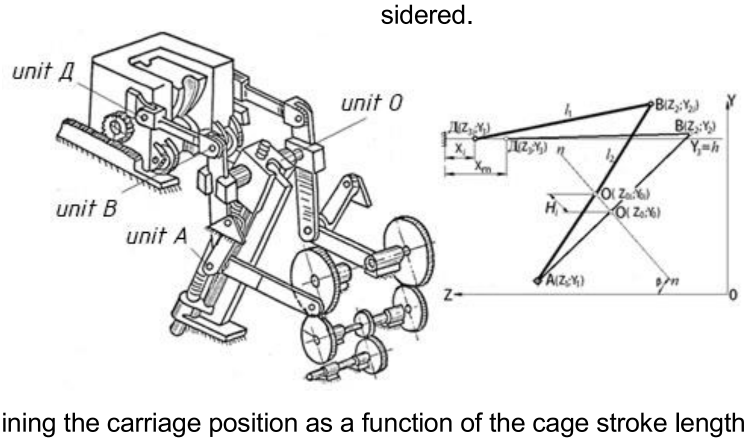

Fig. 9. Before determining the carriage position as a function of the cage stroke length

In this case, the center 0 of the double- arm lever joint occupies its lowest position on the line *n – n*, which makes an angle β with the horizontal and has coordinates z_0 and y_0.

Let's define the coordinates z_{2i} and y_{2i} of the hinge B of a double-arm lever occupying an arbitrary position. It is known that

$$\frac{y_{2i}-y_1}{y_{0i}-y_1}=\frac{z_{2i}-z_1}{z_{0i}-z_1}, \quad (27)$$

$$l_2=\sqrt{(z_1-z_2)^2+(y_{2i}-y_1)^2}, \quad (28)$$

where l_2 – length of the double-arm lever;

z_1 and y_1- coordinates of hinge A.

A joint consideration of (27) and (28) leads to the expressions

$$z_{2i}=z_1-\frac{l_2}{\sqrt{1+q_i^2}};\ y_{2i}=y_1-\frac{l_2 q_i}{\sqrt{1+q_i^2}}. \quad (29)$$

Here $q_i=\frac{y_{0i}-y_1}{z_{0i}-z_1}$ is a dimensionless parameter that characterizes the magnitude of the displacement of the center 0 along the guide line *nn*.

Point D lies on the line $y_3=h$ at a distance l_1 from the center of the hinge B (l_1 - the length of the upper connecting rod of the drive mechanism), therefore the coordinate of z_{3i} the point Д$_3$ is found from the equation

$$(z_{3i}-z_{2i})^2+(h-y_{2i})^2={l_1}^2, \quad (30)$$

substituting into (30) the values of the coordinates y_{2i} and z_{2i} dependencies (30), we obtain

$$\left(z_{3i}-z_1+\frac{l_2}{\sqrt{1+q_i^2}}\right)^2={l_1}^2-\left(h-y_1+\frac{l_2 q_i}{\sqrt{1+q_i^2}}\right)^2. \quad (31)$$

After transformations, we arrive at an equation containing the unknown quantity q_i

$$q_i^2\left(F^2-4{l_2}^2(h-y_1)^2\right)-8q_i{l_2}^2(z_{3i}-z_1)(h-y_1)+F^2-4{l_2}^2(z_{3i}-z_1)^2=0, \quad (32)$$

where $F=(z_{3i}-z_1)^2-{l_1}^2+(h-y_3)^2+{l_2}^2$,

The coordinate of z_{3i} point D in the Z0Y system (Fig. 9) can be represented in the following form:

$$z_{3i}=\mathrm{x}_m+\lambda_0-\mathrm{x}_i. \quad (33)$$

where λ_0 is a constant value that depends on the choice of the coordinate system and the parameters of the drive mechanism

$$\lambda_0=\sqrt{{l_1}^2-\left(h-y_1+\frac{l_2 q_0}{\sqrt{1+q_i^2}}\right)^2}+z_1-\frac{l_2}{\sqrt{1+q_i^2}}.$$

The found solution of equation (32) corresponds to the desired position of the swing center O_i, at which the stroke length of the working cage is equal to x_i.

Let us define the relationship between the parameter q_i and the movement of the carriage H_i from its lowest position. Let us represent the coordinates of the center of swing z_{0i} and y_{0i} in the following form:

$$z_{0i}=z_0+H_i cos\beta;\ y_{0i}=y_0+H_i sin\beta. \quad (34)$$

Then

$$q_i=\frac{y_0+H_i sin\beta-y_1}{z_0+H_i cos\beta-z_1}. \quad (35)$$

After some transformations we have

$$H_i=\frac{(y_0-y_1)-q_i(z_0-z_1)}{q_i cos\beta-sin\beta}. \quad (36)$$

Thus, solving equation (32) for a series of numerical values x_i (in ascending order of index i from 1 to N) the corresponding values of the dimensionless parameter are determined q_i, and depending on (36) the carriage movement H_i necessary for rolling a conical pipe of given parameters is determined.

As an example, Fig. 10 shows a graph of the change in the length of the working stand stroke required for forming a conical pipe 56x4 – 38x1 with a length of 3000 mm on the KhPTK-40 mill at a feed of 4 mm with a working part length of x_m=425 mm. Fig. 11 shows the law of carriage motion (curve 1).

To roll a tapered pipe with a straight generatrix, it is necessary to perform uneven movement of the carriage along the guides. This necessitates the installation of mechanisms with an adjustable gear ratio, which significantly complicates the design of the mill and reduces its reliability.

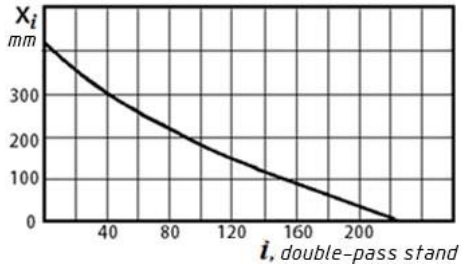

Fig. 10. Change in the length of the stand stroke when rolling a pipe 56x4 – 38x1 with a length of 3000 mm

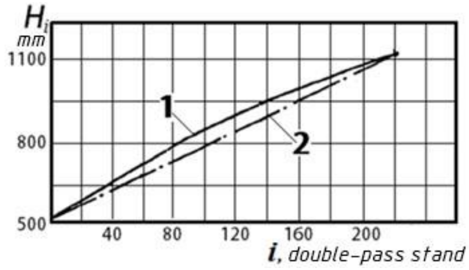

Fig. 11. Moving the carriage H_i when rolling a pipe 56x4 – 38x1 with a length of 3000 mm: 1 – theoretically; 2 – experimentally

Example of calculation of setting the drive mechanism of the KhPTK-75 mill for rolling current collector rods of ZIU-9 trolleybuses (pipe 51x3.5 - 25x3.2; length 4475 mm; material steel 30 KhGSA).

Billet dimensions . Since the finished pipe has a significant difference in diameters, the diameter and wall thickness of the billet are taken equal to the corresponding dimensions of the maximum cross-section of the pipe being rolled.

Calibration of work rolls. Linear-conical calibration is used, R_k=25.5 mm, R_1=12.5 mm, x_m=609 mm (length of the working part of the calibers-half disks of the KhPTK-75 mill). The dependence $R(x)$has the form

$$R(x) = 25{,}5 - \frac{25{,}5-12{,}5}{609}x = 25{,}5 - 2{,}135 \cdot 10^{-2}x, \text{ mm}$$

The profile of the product being formed. The pipe has a conical shape. The radius of the outer surface is described by the relationship

$$Y(z) = 25{,}5 - \frac{25{,}5-12{,}5}{4475}z = 25{,}5 - 2{,}905 \cdot 10^{-3}z, \text{ mm}$$

Changing the wall thickness of the finished product. The current collector rod tube has a wall thickness that varies linearly from t=3.5 to t=3.2 mm, so

$$t(z) = 3{,}2 + \frac{3{,}5-3{,}2}{4475}z = 3{,}2 + 6{,}7 \cdot 10^{-5}z, \text{ mm}$$

The size of a single feed of the pipe billet is taken equal to m=5 mm.

***The dependence* z(x) *is established from the condition* $R(x) = Y(z)$.** For the pipe being formed and the calibers used

$25{,}5\text{-}2{,}135 \cdot 10^{-2}x = 25{,}5\text{-}2{,}905 \cdot 10^{-3}z$,

z = 7,3480xmm.

Mandrel profile

$$R(x) = \frac{x}{609}(3{,}5\text{-}3{,}2\text{-}25{,}5 + 12{,}5) + 25{,}5\text{-}3{,}5,$$

$R(x) = 22\text{-}2{,}0854 \cdot 10^{-2}x$, mm.

Calculation of the function of changing the stroke length of the working stand. The results of calculating the installation parameters of the drive mechanism of the KhPTK-75 mill for rolling a tapered pipe 51x3.5 - 25x3.2, 4475 mm long are given in Table 2, where it is indicated:

x– current value of the length of the i-th double run of the stand – x_i, mm;

dx– change in stroke length – Δx_imm;

z– coordinate $z_i$mm;

Rx– outer surface of the current pipe cross-section – R_x, mm;

q– parameter value q_i for the calculated value Δx_i;

H– carriage movement from its lowest position – H_i, mm.

The parameter $q_i$was calculated for the lever drive system of the KhPTK-75 mill. Its numerical values are given in Table 2.

The gear ratio of the kinematic gearbox $U_p$is determined based on the condition of its stepwise regulation (the number of steps is assumed to be k= 5).

From *N* = 580 double moves of the stand, the values i=1; N/k; $2N/k$; $3N/k$; ...; *N are selected* , namely i=l, 116, 232, 348, 464, 579. These double move numbers correspond to the coordinates of the carriage position H_1 = 387,8; H_{348} = 867,6; H_{116} = 552,0; H_{464} = 1033,2; H_{232} = 709,1; H_{579} = 1209,0.

The gear ratios of the regulating stages of the kinematic gearbox are equal (the pitch of the carriage movement screw t=10 mm):

$$U_1 = \frac{580}{552{,}0-387{,}8} \cdot \frac{10}{5} = 7{,}06; \qquad U_4 = \frac{580}{867{,}6-709{,}1} \cdot \frac{10}{5} = 7{,}32;$$

$$U_2 = \frac{580}{709{,}1-552{,}0} \cdot \frac{10}{5} = 7{,}38; \qquad U_5 = \frac{580}{1209{,}0-1033{,}2} \cdot \frac{10}{5} = 6{,}60.$$

$$U_3 = \frac{580}{867{,}6-709{,}1} \cdot \frac{10}{5} = 7{,}32.$$

The research results presented above were also used in the development of methods for calculating technological parameters for adjusting the HPTC mills in the manufacture of: tubular products of variable cross-section for special power plants ordered by the enterprise NPO "TECHNOMASH" (pipe 7x0.3–3x0.3, length 3000 mm); special tubular products of variable cross-section for shipbuilding enterprises.

Improvement of mechanisms and units of the HPTC mill. ***A significant simplification of the stereometry*** of the drive mechanism of the HPTC mill while simultaneously reducing material consumption, increasing maneuverability, reliability and durability can be achieved by using mechanisms with higher kinematic pairs in the line of moving the stand with stable positioning of its position during the feeding and turning operations, in particular internal gear wheels with a gear ratio of 2 and worm gears.

Table 2. Results of calculation of installation parameters of the drive mechanism of the KhPTK-75 mill for rolling a tapered pipe 51 x3.5 - 25x3.2, length 4475 mm

i	x, mm	dx, mm	z, mm	Rx, mm	q, mm	H, mm
1	607.38	1.62	11.91	12.5	−,43E+01	387.8
20	577.46	1.54	231.78	13.2	−,46E+01	416.2
40	547.57	1.46	451.41	13.8	−,49E+01	445.5
60	51909	1.39	660.69	14.4	−,53E+01	474.1
80	491.83	1.34	861.01	15.0	−,57E+01	502.2
100	465.63	1.29	1053.48	15.6	−,61E+01	530.0
120	440.39	1.24	1238.99	16.1	−,66E+01	557.5
140	415.99	1.20	1418.27	16.6	−,72E+01	584.8
160	392.35	1.16	1591.95	17.1	−,78E+01	611.9
180	369.41	1.13	1760.54	17.6	−,85E+01	639.0
200	347.10	1.10	1924.50	18.1	−,93E+01	666.0
220	325.36	1.07	2084.20	18.6	−,10E+02	692.9
240	304.16	1.05	2239.97	19.0	−,11E+02	719.9
260	283.46	1.02	2392.12	19.4	−,13E+02	747.0
280	263.21	1.00	2540.90	19.9	−,15E+02	774.2
300	243.39	0.98	2686.53	20.3	−,17E+02	801.5
320	223.97	0.96	2829.23	20.7	−,20E+02	828.9
340	204.93	0.94	2969.17	21.1	−,24E+02	856.5
360	186.24	0.93	3106.52	21.5	−,30E+02	884.3
380	167.88	0.91	3241.43	21.9	−,40E+02	912.4
400	149.83	0.90	3374.04	22.3	−,61E+02	940.7
420	132.08	0.88	3504.47	22.7	−,12E+03	969.3
440	114.61	0.87	3632.82	23.1	−,20E+04	998.1
460	97.41	0.85	3759.21	23.4	0.14E+03	1027.3
480	80.47	0.84	3883.73	23.8	0.67E+02	1056.9
500	63.76	0.83	4006.47	24.1	044E+02	1086.8
520	47.29	0.32	4127.51	24.5	0.33E+02	1117.1
540	31.04	0.81	4246.92	24.8	0.27E+02	1147.8
560	15.00	0.80	4364.78	25.2	0.22E+02	1179.0
Tubing has been formed at N=579 double steeps .						

* Every twentieth value of all parameters is printed

The cold rolling mill for long pipes of variable cross-section [7] (Fig. 12) includes a stand 1 with work rolls, a mechanism 2 for its reciprocating movement, a rotary -feed device 3 with a screw mechanism 4 for moving the workpiece chuck 5, on the nut of which a gear wheel 6 is fixedly fixed, which receives rotation, for example, from a Maltese mechanism. The work rolls can rotate by means of a kinematic connection of rails with a worm cut 7 and gear wheels 8 fixed on their necks. The mechanism for reciprocating movement of the stand includes two carriers 10 driven by the engine 9, each of which has a gear crank wheel 11 with a crank pin 12. On it, with the possibility of rotation, a slider 13 is located, installed in a vertical groove of the stand frame. The gear crank wheel is in internal engagement with a double-crown gear wheel 14, which has twice the number of teeth and the outer ring of which is connected by means of a wheel 15 to a shaft 16 passing through a stationary rack with a worm gear and an adjustable gear clutch 17 connected to it. The other end of the shaft is connected through a gearbox 18 to a gear wheel 6 and, by means of an additional shaft 19 and a gearbox 20, to a screw 21 of the mechanism for moving the mandrel 22. The rotation of the carrier 10 by means of the motor 9 leads to a reciprocating movement of the cage by an amount that depends on the angle of rotation of the double-crown gear wheel 14 from the initial position, at which the trajectory of the movement of the crank finger is placed horizontally. When the double- crown gear wheel 14 rotates, the trajectory of the crank pin movement is rotated, which, if there is a kinematic connection between it and the cage using the slider 13, causes a change in the length of the cage stroke. Its minimum value, equal to zero, occurs when the double-crown gear wheel 14 is rotated by an angle of 90° (while the crank pin 13 moves vertically). During the open state of the feed throat and the rotation of the workpiece, the rotary -feed device 3 is triggered. The rotation of the nut is transmitted to the double-crown gear wheel by means of the gear wheel 6 fixed on it, the transmission shafts 16, the gearbox 18 and the gear wheel 15. The extreme rear position of the gauges is fixed by constantly rotating them to this position through a worm gear, which includes stationary rails 7, which receive rotation from shafts 16, and gear wheels 8. To maintain the constant mutual arrangement of the gauges and the mandrel, the mandrel rod is synchronously moved by a screw mechanism, which receives rotation from shaft 16 through an additional shaft 19. The magnitude of the change in the stroke length of the working stand is set by the gear ratio of the gearbox 18. The presence of adjustable gear couplings 17 allows you to adjust the extreme fixed position of the gauges. The proposed kinematic connection of the rotary -feed mechanism and the mechanism of reciprocating movement of the stand allows you to improve the quality of the products being rolled and the reliability of the mill as a result of the fact that the change in the stroke length of the stand is carried out with the feed and rotation throat open. The presented layout provides a significant reduction in overall dimensions and metal consumption of the mill as a whole.

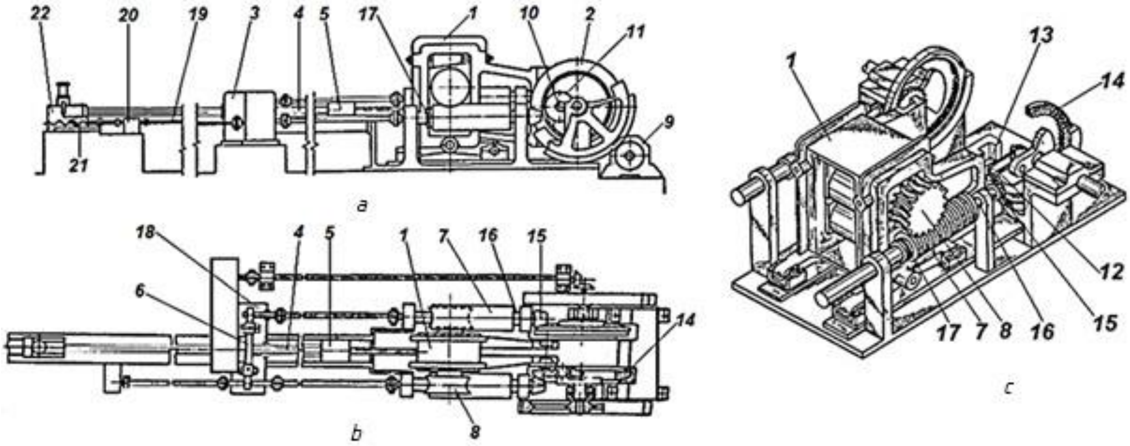

Fig. 12. Cold rolling condition of long pipes of variable cross-section: a – general view; b – top view; c – mechanism of reciprocating movement of the stand

Optimization of the design of the working frame elements. The design of the working frame of the HPTK mill, its rigidity and other operating parameters largely determine the quality of the products of variable cross-section that are manufactured. The traditional frame (Fig. 13, *a*) has a massive base, which contributes to increasing the stability of its reciprocating motion and reducing wear of the supporting surfaces.

The inflows 7 are designed to connect the stand with the drive mechanism, and the inflows 8 with the balancing device. It is equipped with a pressure device 2, which is installed between the upper roll cushion 3 and the frame 1. The device includes punches 4, shear elements placed in the wedge-matrixes 5, which are simultaneously wedges that provide changes in the positions of the upper roll cushions 3. The wedges 5 move along the inclined planes of the upper roll cushions in directions parallel to the rolling axis. The wedges are fixed by screws 6 mounted in the racks of the side frames of the frame 1. As a result of wear of the working rolls and bearings, as well as plastic deformation of the elements of the devices 2, the inter-roll gap increases, which causes additional movement of the wedges 5, which causes a shift in the zones of interaction of the pressure devices with the roll cushions. The latter complicates the process of regulating the solution between the rolls, as a result of which the specified parameters of the deformation cell change [8]. The formation of the stereometry of the instantaneous deformation cell (MOD) is influenced to varying degrees by such indicators of the moving stand assemblies as the mutual orientation of the roll axes and the rolling axis. Calculation schemes that determine the consumer characteristics of the finished product are erroneously built on the assumption that the half-sections of the MOD, moving along the mandrel axis, are located in a plane perpendicular to the rolling axis; are symmetrical; and under the action of rolling forces move in the vertical direction. Due to the differences in the rigid characteristics and wear characteristics of the parts and assemblies that close the power flows in the left and right windows of the frame, the wedges 5 will occupy different positions along the rolling axis, which will lead to skewing and crossing of the roll axes. Thus, when loading the stand of the KhPT-32 mill of the EZTM design with a rolling force of 0.5 MN, the upper roll cushions, depending on the position of the wedges, change their position in the stand windows, causing a skew of its axis, which is characterized by a difference in the position of the centers of symmetry of the bearing supports of up to 17 μm (Fig. 13, *b*).

Distinctive design features of the rational working frame of the KhPTK mill. When creating the design of the working frame, attention was paid to establishing a rational shape of its bed, the possibility of reducing weight while simultaneously increasing the bearing capacity and rigidity of the structure, the possibility of choosing the optimal scheme of the pressure device, and others.

The rational working cage (Fig. 14) consists of an oval-shaped frame 1, in the windows of which a pressure device 2 is mounted, working rolls (upper 3 and lower 4), which are mounted on bearings in the pillows 5 of the upper roll and pillows 6 of the lower one. Oval-shaped frames with internal windows are made in the form of internal 7 and external 8 shells.

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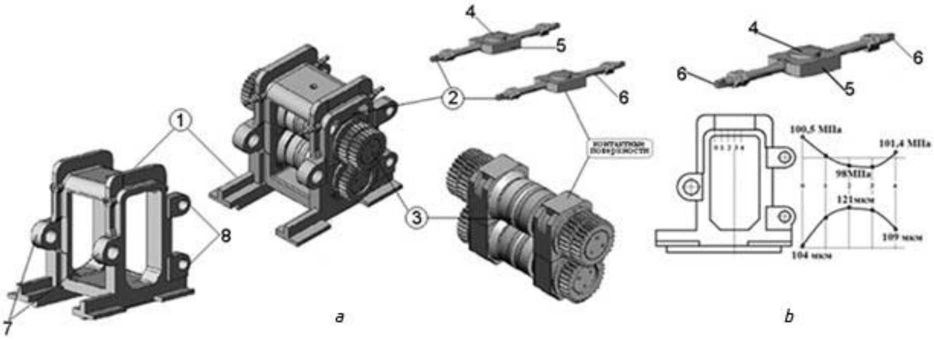

Fig. 13. Working stand of the HPT mill of the EZTM design

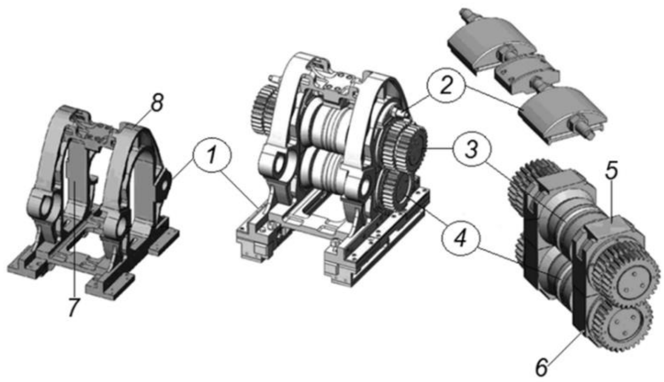

Fig. 14. Rational working stand of the KhPTK mill [9]

Design features of the optimal pressure device. One of the shortcomings of the existing stands of the HPTK mill is that they do not allow the selection of axial gaps in the roll supports, which appears due to wear of the bearings, due to which the relative axial displacement of the roll streams occurs and the shapes of the deformation centers are distorted. This leads to biting of the pipe metal and the appearance of errors in their shapes. In addition, the design of the stands does not allow compensating for errors in processing and assembly of parts, which leads to the appearance of additional loads. Effective management of the rolling process and the exclusion of the appearance of non-technological loads in the elements of the working stand caused by inaccuracy in the manufacture and assembly of parts allows the use of a pressure device of optimal design. Fig. 15 shows the kinematic and structural diagrams of such a pressure device, which contains wedge and screw mechanisms for moving the bearing assemblies of the upper roll. In the structural diagram, the movable MOD is represented by a kinematic pair of the fourth kind.

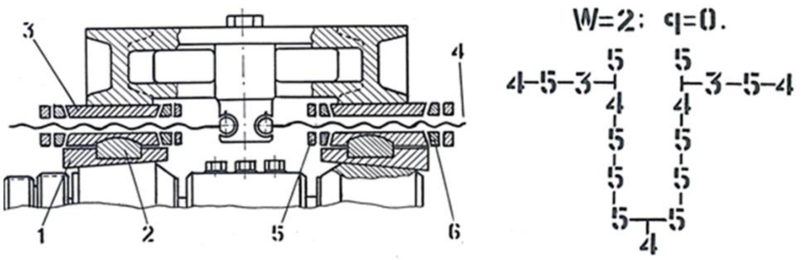

Fig. 15. Kinematic and structural diagram of the pressure device of optimal stereometry

The wedge mechanisms contain wedges 1, moving in a plane perpendicular to the rolling axis, in opposite sides of the roll axis along the inclined contact surfaces of the pillows of the bearing assemblies of the upper roll. Two pairs of compensating inserts with cylindrical surfaces, the axes of one of which 2, installed on the wedges 1, are parallel to the longitudinal axis of the frame, and the axes of the other 3, in contact with the frame, are parallel to the roll axis. Screws 4, fixed in the frame by kinematic pairs of the fourth kind, which provides rotational movements in the spherical holes of the frame and eliminates rotation of the screws relative to their own longitudinal axes, nuts 5 and spherical washers. The optimal scheme of the pressure device is built using structural synthesis methods [10], which satisfies the conditions of unconstrained assembly and indifference to deformations of the base parts, and this allows for effective rolling of long conical pipes, eliminating the manifestation of non-technological loads in the elements of the working stand; simplifying the adjustment process; increasing the reliability and durability of the stands.

Conclusions. The main difference of the technological process under consideration is the need for a programmatic change in the stroke length of the working rolls (cell), i.e. the values of the displacements of the MOD of the pipe billet, which necessitates the need for discrete changes in the draw coefficients and all energy-power and geometric parameters during the rolling cycle of a long product with variable cross-sectional parameters. Based on the conditions for obtaining the specified geometry, the features of the functioning of the HPTC mill with a drive lever mechanism in relation to the technological and mechanical parameters of the process implementation are revealed. The development of an iterative model of the formation of tubular products of variable cross-section, the lengths of which are many times greater than the sweeps of the caliber stream, is presented, the results of which were used in the development of methods for calculating the technological parameters of the HPTC mill settings in the conditions of pilot production of the State Enterprise "Research and Design and Technological Institute of the Pipe Industry named after Ya.Yu. Osada".

Design solutions for further improvement of equipment elements are considered. In the state of the HPTC [7], the drive of the variable-size stand stroke is carried out by the simplest epicyclic internal gear transmission with two degrees of freedom, and the positioning of the stand elements to perform the feed-turn operation before the start of the next rolling cycle is implemented by a worm gear, which allows improving the stereometry of the unit for the manufacture of long tubular products with variable cross-sectional parameters with a simultaneous reduction in material consumption.

The presented studies on the behavior of MOD elements allowed us to develop design solutions that improve the quality characteristics of the manufacturing process of tubular products with variable cross-sectional parameters, the length of which is many times greater than the sweep of the caliber stream.

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Вахрушева В.С.

Сучасні технології виробництва труб-оболонок тепловиділяючих елементів (ТВЕЛ) з сплавів цирконію та стан виробництва в Україні

Vakhrusheva V.S.

Modern technologies for the production of fuel element cladding tubes (FEEL) from zirconium alloys and the state of production in Ukraine

Анотація. *У теперішній час атомна енергетика зберігає свої позиції як один з основних світових джерел енергії. В Україні передбачається подальший розвиток атомної енергетики тому одним з важливих напрямків є створення власного ядерно паливного циклу(ЯПЦ). Складовою частиною ЯПЦ є виробництво труб-оболонок тепловиділяючих елементів з сплаву цирконію Zr1Nb. Метою роботи є розробка технології, виготовлення дослідних партій труб із сплаву цирконію Zr1Nb в Україні та дослідження їх якості. Методика. Виготовлення труб в виробничих умовах. Дослідження якості труб з використанням оптичної мікроскопії, макроструктурного аналізу, механічних випробувань при кімнатної та підвищеної температурах, оцінка орієнтації гідрідів, корозійні випробування, дослідження тривалої міцності, повзучості. Результати. Вперше в Україні на базі Державного підприємства «Науково-дослідний та конструкторсько-технологічний інститут трубної промисловості ім. Я.Ю. Осади» виконані роботи по розробці технології та виготовленню дослідних партій труб-оболонок тепловиділяючих елементів(ТВЕЛ) з цирконієвого сплаву Zr1Nb розміром Ø9.13× вн. 7.72 мм. Оцінена якість труб згідно з вимогами стандартів ASTM. Комплексні дослідження структури, властивостей показали відповідність вимогам стандартів ASTM. Наукова новизна. Вперше в Україні розроблена технологія та в промислових умовах виготовлені труби–оболонки тепловиділяючих елементів з цирконієвого сплаву Zr1Nb розміром Ø9.13×вн.7.72мм. Показано, що якість труб відповідає вимогам стандартів на труби. Практична значимість. На основі виконаних досліджень можлива організація промислового виробництва в умовах трубних заводів України.*
Ключові слова: *атомна енергетика, труба-оболонка тепловиділяючий елемент, сплав цирконію, технологія, якість.*

Abstract. *At present, nuclear energy retains its position as one of the main world energy sources. In Ukraine, further development of nuclear energy is planned, therefore, one of the important directions is the creation of its own nuclear fuel cycle (NFC). An integral part of the NFC is the production of fuel element cladding tubes from zirconium alloy Zr1Nb. The purpose of the work is the development of technology, the manufacture of pilot batches of tubes from zirconium alloy Zr1Nb in Ukraine and the study of their quality. Methodology. Production of tubes in production conditions. Research of the quality of tubes using optical microscopy, macrostructural analysis, mechanical tests at room and elevated temperatures, assessment of hydride orientation , corrosion tests, studies of long-term strength, creep. Results. For the first time in Ukraine, on the basis of the State Enterprise "Scientific and Design and Technological Institute of Pipe Industry named after Ya.Yu. Osada", work was carried out on the development of technology and the manufacture of pilot batches of tubes-shells of fuel elements (TVEL) from zirconium alloy Zr1Nb with a size of Ø9.13× in. 7.72 mm. The quality of the tubes was assessed in accordance with the requirements of ASTM standards. Comprehensive studies of the structure and properties showed compliance with the requirements of ASTM standards. Scientific novelty. For the first time in Ukraine, a technology has been developed and tubes-shells of heat-generating elements made of zirconium alloy Zr1Nb with a size of Ø9.13×in.7.72mm have been manufactured in industrial conditions. It has been shown that the quality of the tubes meets the requirements of the standards for tubes. Practical significance. Based on the research performed, it is possible to organize industrial production in the conditions of Ukrainian tube plants.*
Keywords: *nuclear power, shell-and-tube fuel element, zirconium alloy, technology, quality.*

Introduction. Nuclear energy accounts for 1/6 of the world's fuel and energy balance and 43% for Western Europe. The growth of nuclear power plant capacities is predicted , primarily in the countries of Asia and the Asia-Pacific region (China, South Korea, India, Japan), some countries of Eastern Europe (Czech Republic, Slovak Republic), as well as a number of countries that are members of the Commonwealth of Independent States (Kazakhstan). Many countries intend to create nuclear power, including: Turkey, Iran, Indonesia, Vietnam [1, 2].

Given the significant role of nuclear energy in energy supply and the low cost of electricity production at nuclear power plants, which is achieved mainly due to the fuel component, it was natural to pose the problem of creating a National Nuclear Fuel Cycle (NFC) in Ukraine, which would guarantee the provision of nuclear power plants with fresh fuel, the supply of which should be independent of political and economic relations [2].

The problem of creating a National Center for the Promotion of Culture in Ukraine is part of a complex of particularly important national tasks.

An integral part of the Comprehensive Program for the Creation of the Nuclear Power Plant is the organization of the production of zirconium rolled products - fuel element cladding tubes and fuel assembly components. Until now, fuel element cladding tubes made of zirconium alloys have not been produced in Ukraine. The technology for manufacturing fuel element cladding tubes is one of the most science-intensive in the theory and practice of pipe production.

The operation of fuel element cladding tubes in the core is carried out in the most extreme conditions: at high operating temperatures, cyclic mechanical and thermal loads, in intense radiation fluxes, in the presence of an aggressive coolant and fuel pellet environment. On this basis, a set of strict requirements is put forward for cladding tubes: high mechanical properties at different temperatures, corrosion resistance in different environments at high pressures and temperatures, the required structure, texture, surface condition, restrictions on the anisotropy of properties, orientation of hydrides, and the presence of fluorine ions on the surface [3, 4].

Purpose and tasks. It is the metallurgical problems of creating a complex of properties of fuel element cladding tubes that determine the requirements for building a technological process. In world practice, technologies for producing fuel element cladding tubes from zirconium alloys were created 50-70 years ago, in this regard, when organizing their production in Ukraine, the achievements of modern science and technology should be taken into account.

Creative generalization of world science made it possible to establish that the most complete complex of metallurgical and technological tasks of production and use of tubes in the core zone of NPPs is reduced to reducing the structural and chemical heterogeneity of metals at all stages of technological processes: metal smelting, manufacturing of billets and tubes, creation of structures of a certain type, which provide increased radiation and corrosion resistance, reduction of hydride embrittlement , improvement of the surface quality of products. The final phase of research and development is the organization of production of fuel rod cladding tubes from zirconium alloys in the conditions of Ukrainian enterprises.

Thus, the need to solve the complex scientific problem of improving the quality of pipes and organizing their production for the core of nuclear power plants (NPPs) in Ukraine determines the relevance of the problem.

Material and methods of research. The main type of reactors used at Ukrainian nuclear power plants are water-water reactors cooled by ordinary water under pressure, VVER-type shell reactors. In the active zones of the reactors under consideration, similar in type but different in design are used, rod fuel elements assembled into assemblies, the tubes of which are made of zirconium alloys Zr1Nb, and U_{O2} pellets with different enrichment in U-235 (up to 5%) are used as nuclear fuel.

Elements of tubular structures widely used in the cores of nuclear reactors, for example, fuel rods, are among the most loaded structural components of the cores of nuclear reactors.

Fuel rods are operated in very difficult conditions: in powerful radiation fields of all types of reactor radiation; at high internal temperatures of the fuel core, reaching 2000...2500°C in the center, in the cladding - 300...350°C, at fairly high coolant pressures up to 16...17 MPa, with active external corrosion action on the cladding from the coolant side and internal - from the fuel side, gaseous and volatile uranium fission products, under the action of complex stresses on the fuel rod cladding tube material , swelling fuel, thermal cycles, radiation deformation, as well as hydrodynamic effects of high-speed coolant flow. [3]. Therefore, the work carried out comprehensive testing of the metal using optical microscopy, quantitative metallography, evaluation of mechanical properties at room and elevated temperatures in the longitudinal and transverse directions, corrosion tests, evaluation of hydride orientation, ultrasonic and eddy current control. In addition, creep and low-cycle fatigue were investigated.

Research results. In Ukraine, on the basis of the State Enterprise "Scientific Research and Design and Technological Institute of Pipe Industry named after Ya.Yu. Osada" (SE "NDTI"), work was carried out on the development of technology and manufacturing of shell tubes and fuel assembly products from zirconium alloy Zr1Nb of Ukrainian production. During the work in this area, the following complex of works was carried out within the framework of the Program for the creation of the Nuclear Power Plant:

- the main technological schemes for the pilot-industrial production of casing pipes and rods have been developed in relation to the domestic production base;
- several experimental batches of fuel element cladding tubes made of Ukrainian-made Zr1Nb alloy were manufactured at various Ukrainian pipe plants under industrial production conditions;
- a comprehensive assessment of the quality of experimental batches of pipes was carried out, confirming their compliance with the main indicators with the requirements of regulatory documentation (ASTM standards);
- a package of the first versions of regulatory documentation for the production of pipes and rods (technical specifications for pilot batches of pipes and rods, technological instructions, control methods) was developed and approved;
- a set of measures and technical solutions has been developed to modernize existing and purchase new equipment, ensuring the efficiency of the technological process and product quality;
- the basic technological scheme of industrial production of zirconium rolled products in Ukraine has been determined.

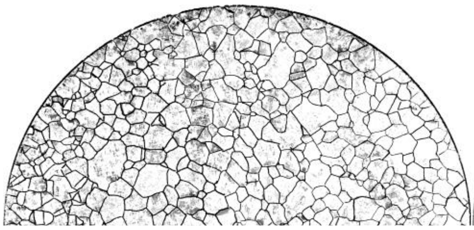
As part of the work performed, a technological scheme for the manufacture of fuel element cladding tubes using new elements was proposed:

- use of cast pipe billets obtained by various smelting methods: electron beam, vacuum arc and centrifugal casting;
- high-temperature pressing in the β-region of cast pipe blanks with large degrees of deformation;
- hardening by rolling heating.

In Ukrainian pipe plants, experimental batches of cladding tubes and rods that complete fuel assemblies were rolled in industrial conditions.

New elements of the technological scheme for pipe production include, first of all, the production and use of cast pipe billets ∅150-200 mm and ∅80 mm, manufactured by various methods: electron beam remelting with electromagnetic stirring, vacuum arc remelting, and centrifugal casting.

Cast pipe blanks were comprehensively investigated: macro- and microstructure, chemical composition, mechanical properties, hardness were evaluated. Quantitative metallography and electron microscopic studies were performed [5, 6]. Fig. 1 and 2 present the macro- and microstructure of cast billets of different smelting methods.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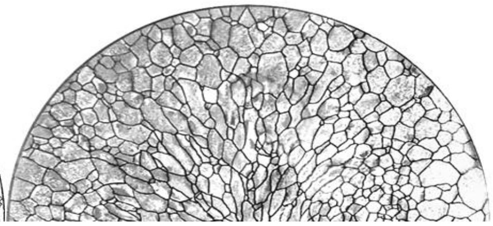
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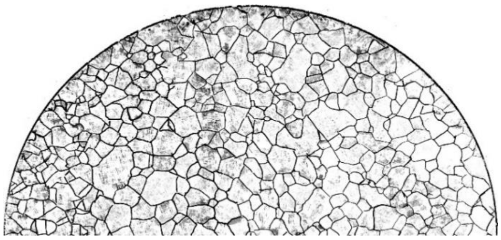
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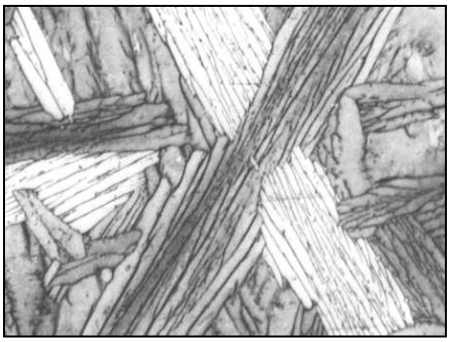
Fig. 1. Macrostructure of cast pipe billets of different smelting methods: a – electron beam remelting (EBR); b – electron beam remelting with electromagnetic stirring (GEMP);c – vacuum arc remelting (VDP)

The macrostructure of the Zr1Nb alloy melted by vacuum arc remelting (VDP), compared to electron beam remelting (EBR), is more homogeneous and fine-grained, as evidenced by the sizes of the α-zirconium and β-niobium plate packages and their periodicity (Fig. 3).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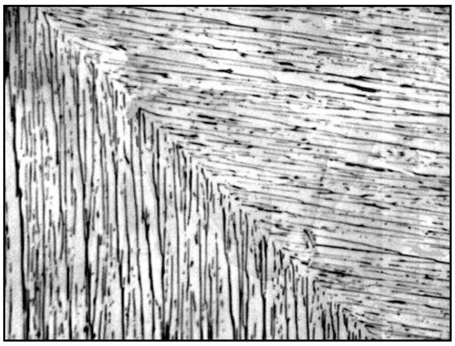
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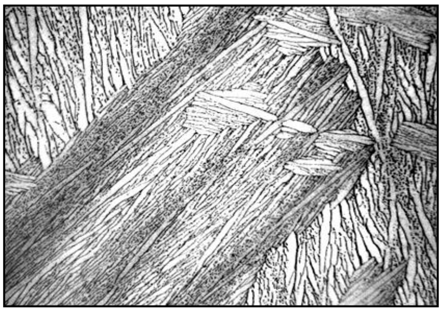
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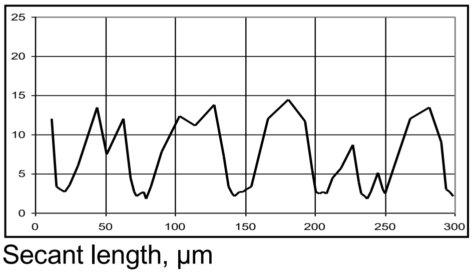
Fig. 2. Microstructure of cast pipe billets of different smelting methods: a - E P P; b - GEMP; c – VDP



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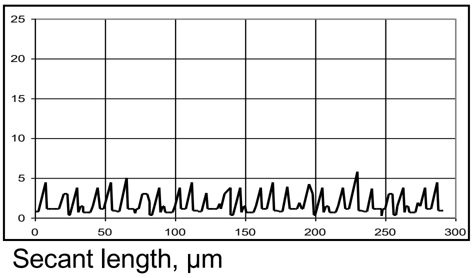

b

Fig. 3. Distribution of the width of the plates in the batch structure of castings of different smelting methods: a – EPP casting from Zr1Nb alloy; b – VDP casting

In the structure of cast blanks obtained by the VDP method, as compared to EPP, the size of the plates and the period of alternation of groups in packages are several times smaller and are 6...8 μm, as compared to 20...30 μm in EBR.

The characteristics of centrifugally cast pipe blanks according to the same parameters occupy values intermediate between EBR and VDP.

Special attention during the development of the technological scheme for the production of pipes was paid to the hot reshaping of cast pipe blanks [5]. The new solution of high-temperature pressing in the β-region with large plastic deformations was preceded by a set of studies on the influence of the deformation temperature, heating rate, degree of metal drawing (deformation), coating quality, assessment of the size of the gas-saturated layer, etc. Assessment of the properties of the metal structure by various methods made it possible to choose the optimal temperatures and degrees of metal deformation during hot pressing. Fig. 4 shows the metal structure of hot-pressed pipes at deformation temperatures in the range of 850...1100°C. The metal structure of pipes measuring ∅59×12 mm (trex pipes) is different - from the unrecrystallized one obtained at a deformation temperature of 850°C (Fig. 4 a), to bainite (Fig. 4 b) and martensitic (Fig. 4 c).

a b c

Fig. 4. Structure of hot-pressed pipes, at a deformation temperature of 850°C, not recrystallized, (a) to bainite (b) and martensitic (c)

In the manufacture of fuel element cladding tubes from zirconium alloys, the level of plasticity, which is determined by the structural state obtained at the stage of hot deformation, has a significant impact on the behavior of the metal during cold deformation. The technology developed at SE "NDTI" allows for one cycle of hot pressing to obtain trex tubes with a homogeneous, finely dispersed structure [6]. This creates the prerequisites for increasing the degree of deformation during rolling of tubes at the first cold re-section.

In the course of the research, it was established that the formation of a martensitic-type structure during hot deformation provides higher technological plasticity during the first cold reshaping.

A comprehensive assessment of the quality of fuel rod cladding tubes rolled using new technology elements showed that the tubes meet the requirements of ASTM standards in terms of their main parameters [7].

In addition to traditional tests regulated by standards, such as:

- estimation of geometric dimensions;
- evaluation of mechanical properties at room and elevated temperatures in the longitudinal and transverse directions;
- corrosion tests in steam under pressure;
- assessment of hydride orientation;
- determination of the anisotropy coefficient;
- ultrasonic control;

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- eddy current control;
- surface roughness assessment;
- the presence of fluoride ions on the surface,

additional studies have been performed:

- low-cycle fatigue;
- creep;
- long-term corrosion resistance tests;
- electron microscopic studies;
- scanning electron microscopy to assess surface quality.

Analyzing the obtained results of the research on the quality of casing pipes, it should be noted the following. Research on the mechanical properties of pipes tested during stretching in the longitudinal and transverse directions at temperatures of 20°C and 350°C showed high plasticity with a high level of strength characteristics, which significantly exceed the requirements of ASTM standards and other standards (Table 1).

Table 1 - Mechanical properties of casing pipes of size 9.13× in 7.72 mm from Zr1Nb alloy

Manufacturer	Mechanical properties					
	Longitudinal direction			Transverse direction		
	Tensile strength σ_B, H/mm^2	Yield strength σ_{02}, H/mm^2	Relative lengthening δ, %	Tensile strength σ_B, H/mm^2	Yield strength σ_{02}, H/mm^2	Relative lengthening δ, %
Test temperature 20°C						
oh gti	580-590	415-425	34-36	550-600	500-533	16.1-16.7
JSC "NPTZ"	615-650	480-495	30-33	605-650	560-595	13-13.3
REQUIREMENTS TU 95-405-89 no less than	410	240	20	–	–	12
The temperature is 380°C						
oh gti	–	–	–	226-235	222-226	27-30
JSC "NPTZ"	235-265	135-153	530-560	225-240	190-200	27-36
Requirements TU 95-405-89 no less than	–	80	–	148	130	33

The higher level of mechanical properties is due to the significantly increased oxygen content in the Zr1Nb alloy (0.12...0.16%). Studies conducted at the National Scientific Center "Kharkiv Institute of Physics and Technology" at the electron microscopy level have established that this has a positive effect on the behavior of the metal when irradiated.

The values of the increase on samples of Ukrainian-made pipes of different melts and manufacturing methods are close to each other and are 14-16 m^2 /dm^3, which does not exceed the requirements of TU and ASTM standards.

The study of corrosion of Ukrainian-made Zr1Nb alloy pipes under three different autoclaving regimes showed that the corrosion rates are similar for the materials under study. An additional test regime for 72, 500, 1000 hours did not reveal any signs of nodular corrosion, fracture sites, or surface whitening (Fig. 6).

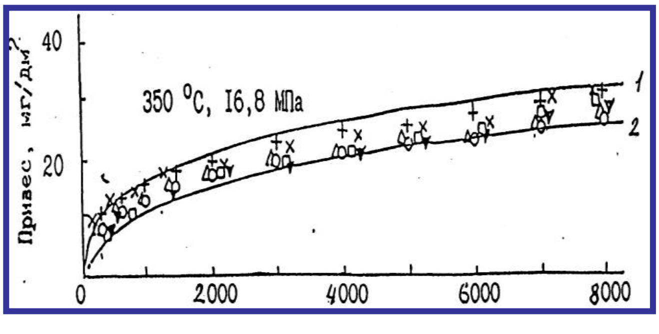


Fig. 6. Corrosion kinetics of samples of experimental batches of fuel element cladding tubes: 1 - alloy E-110; 2 - alloy CTC (calcium-thermal zirconium)

Studies of long-term strength and creep at loads from 157 to 227 MPa and test temperatures of 380°C showed higher plasticity of the Zr1Nb alloy in creep resistance tests. The time to failure - the moment of the appearance of the first microcracks at P=157 MPa for pipes made of Zr1Nb alloy was 1206 hours, the average creep rate ε=3-10-4%h, and for the E-110 alloy - 1170 hours at ε = 5-10-3%h (Fig. 7).

The microstructure of the finished pipes, evaluated using optical and electron microscopy, regardless of the technological options for production, is equiaxed. recrystallized grains of the α-phase with dispersed inclusions of the β-Nb phase (Fig. 8), grain size 3-10 μm. The recrystallization processes were complete, which was confirmed by electron microscopic studies.

Most grains (90%) are oriented with the basal plane (0001) almost parallel to the pipe surface, as shown by the texture study data.

The average orientation coefficient of hydrides in rolled pipes is 0.2-0.35 (Fig. 9).

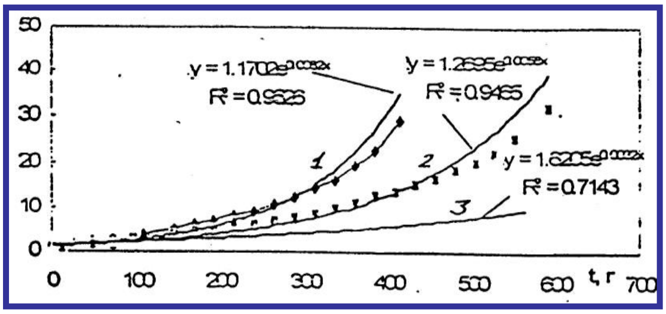
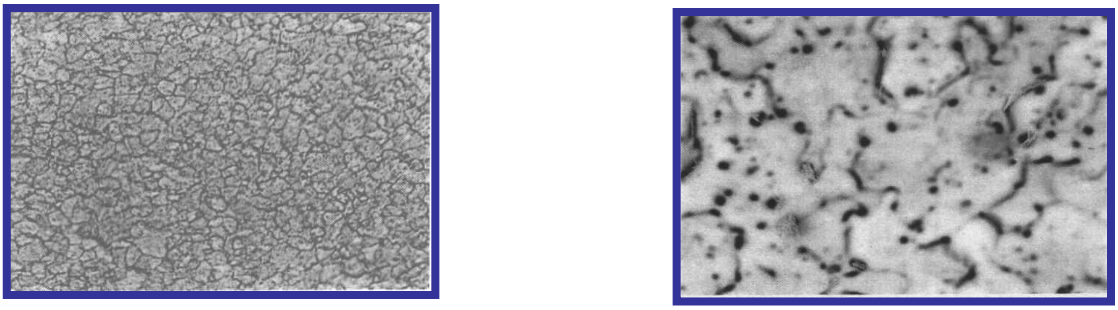


Fig. 7 Creep curves of fuel element cladding tube samples: 1 - alloy KTC 110 (P=221 MPa); 2 - alloy KTC 110 (P=219 MPa); 3 - alloy E 110 (P=119 MPa).



a b

Fig. 8. Microstructure (a), ×200 and separation of the second phase (b), ×1000 (b) in pipes with dimensions of 9.13×7.72 mm made of ZrlNb alloy

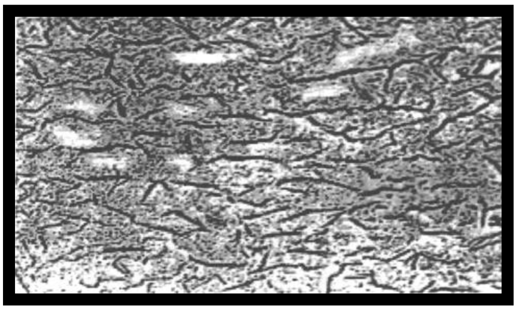


Fig. 9. Orientation of hydrides in the metal of pipes measuring 9.13×7.72 mm in size made of ZrlNb alloy

Experimental batches of tubes were used to manufacture fuel rod models, which were tested in conditions close to reactor conditions. All models withstood the tests.

The main results of the work carried out to develop the technology of zirconium rolling are briefly presented above. The entire complex of works on the smelting of the billet, chemical treatment, calculations of tool calibrations, acoustic emission studies on the selection of the limiting degrees of deformation, studies of crack resistance, etc. are not reflected.

Unfortunately, in recent years, work in this area has been discontinued in Ukraine.

The plant, which was supposed to house the production of zirconium rolled products and other types of pipes for the needs of nuclear energy, - the Experimental Plant of the Pipe Institute (OZ GTI, and then DZPT) - was completely destroyed, and the Pipe Institute (SE "NDTI" named after Ya.E. Osada) is in critical condition.

Ukraine still has scientific and production potential that needs to be used in the near future. For example, the production of zirconium rolled products can be located in Nikopol at the OSKAR plant (the former shop for the production of pipes for nuclear power TVC-4 PTZ).

Conclusions

The conducted research allowed us to develop a basic technological scheme for the production of zirconium rolled products: fuel element cladding tubes, zirconium alloy rods. The first version of regulatory documentation was created.

With a state approach, in the context of the approved decision to build a nuclear fuel production plant and the availability of a zirconium raw material base in Ukraine, the creation of the production of components for the manufacture of fuel assemblies, primarily fuel element cladding tubes, should not be postponed for decades. It is necessary to use the achievements of the Ukrainian scientific school in the field of obtaining zirconium alloys and rolling from them.

The primary tasks for organizing the production of zirconium rolled products are:

1. Obtaining zirconium sponge and ingots from it.
2. Creation of production facilities for the production of ingots and trex pipes.
3. Reconstruction and acquisition of equipment for rolling and quality control of fuel rod cladding tubes at the OSKAR enterprise (Nikopol, former TVC4).
4. Resume research and development work to support the organization of production and rolling of zirconium and its alloys in Ukraine.

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Удосконалення методики розрахунку таблиць прокатки для безперервних безоправкових станів гарячої прокатки труб

Shifrin E.I., Gulyaev Y.G.

Improvement of the method for calculating rolling tables for continuous mandrel-free hot pipe rolling mills

Анотація. *Від того, яким чином при розрахунках параметрів налаштування і калібровок валків калібрувальних і редукційних станів гарячої безоправкової прокатки труб, у певній мірі залежить їх точність по товщині стінки і діаметру. До значущих факторів, які мають значний вплив на процес формозмінення труб при поздовжній прокатці в калібрах безперервного безоправкового стана відносяться способи обробки калібрів валків (індивідуальна обробка кожного валка окремо або обробка калібрів у зборі). Розроблено нову методику розрахунку таблиць прокатки труб у даних станах, яка враховує технологію нарізання калібрів прокатних валків. Доведено, що використання удосконаленої методики розрахунку таблиць прокатки на калібрувальних і редукційних станах різної конструкції дозволяє виготовляти гарячекатані труби з суттєвим підвищенням точності геометричних розмірів і зниженням витрат металу.*
Ключові слова: *калібровка валків, редукційний стан, калібрувальний стан поздовжня безоправкова прокатка, таблиця прокатки.*

Abstract. *The way in which the setup parameters and fork calibrations of calibration and reduction mills for hot mandrelless pipe rolling are calculated depends to a certain extent on their accuracy in terms of wall thickness and diameter. Significant factors that have a significant impact on the process of pipe forming during longitudinal rolling in the gauges of a continuous mandrelless mill include the methods of processing roll gauges (individual processing of each roll separately or processing of gauges as a whole). A new methodology has been developed for calculating pipe rolling tables in these mills, which takes into account the technology of cutting roll gauges. It is proved that the use of an improved methodology for calculating rolling tables on calibration and reduction mills of various design allows the production of hot rolled pipes with a significant increase in the accuracy of geometric dimensions and a reduction in metal consumption.*
Keywords: *roll calibration, reduction mill, calibration mill, longitudinal mandrelless rolling, rolling table.*

Dedicated to Professor, Doctor of Technical Sciences GENADIY IVANOVYCH GULYAEV - an outstanding Ukrainian scientist, one of the founders of the theory of pipe reduction

State of the problem. The main issue of the technology of rolling pipes on continuous mandrel -free longitudinal rolling mills (as well as on other pipe rolling mills) is the possibility of manufacturing pipes on these mills with high accuracy of wall thickness and diameter, which largely depend on how the main technological parameters of the forming process are set. This also includes the method of calculating rolling tables.

To date, the following calculation scheme for tables of continuous, burr-free calibration (reduction) of pipes is most often used.

The mode of distribution of partial deformations $\varepsilon_i$across the cages is set.

The ovality value of the calibers is set λ_i. In assigning the values, λ_i the accumulated empirical experience of operating a specific pipe rolling unit is used, or calculation methods are used. In determining the value λ_i by calculation, the formula of G.I. Gulyaev is most often used [1]

$$\lambda_i = \left(\frac{1}{1-\varepsilon_i}\right)^{q_i}, \qquad (1)$$

where q_i is an empirical coefficient that depends on the number of rolls in the stand and the steel grade of the deformed pipe.

Further, using the assumption that the average diameter of the caliber D_i is equal to the sum of its height h_i and width b_i [5]

$$D_i = b_i + h_i, \qquad (2)$$

or the method proposed in [1], calculate the height h_i and width b_i of each gauge, as well as the values of the quantities that determine the dimensions of the gauge (radius R_i and eccentricity e_i for each of the gauges that are cut individually; cutter diameter D_{fi} and cutter offset F_i for each of the gauges that are cut in an assembly).

The disadvantage of this method of calculating rolling tables is that the value of the broadening index δb_i (which largely determines the level of transverse wall difference of finished pipes) of the continuous state is not an independent variable in each stand, and its value is determined by the initially selected mode of distribution of partial deformations ε_i and the ovality of the calibers λ_i.

At the same time, it was established that, given the initially given law of distribution of partial deformations ε_i across the stands of a continuous mill, the use of assumption (2) gives a significant error in determining the geometric parameters of the gauges, because the ovality of the gauges λ_i also significantly depends on the technology of cutting them on the rolls [6].

Improved method for calculating rolling tables for continuous, straight-run hot-rolling pipe mills.

Based on the shortcomings that were identified when using the current methods for calculating rolling tables for hot-rolled pipes on continuous longitudinal rolling mills, two practical conclusions were made regarding the development of a new, different from the above, concept of building rolling tables for coreless deformation of pipes.

Firstly, when developing tables for specific pipe sizes, it is advisable to initially specify the values of the expansion indices δb_i in continuous state cages, and the ovality of the calibers λ_i is determined as a function of the values of partial deformations ε_i and δb_i.

Secondly, the ovality value λ_i must be determined depending on the technology of caliber manufacturing. This approach to compiling tables of continuous mandrel-free pipe rolling is protected by patents of Ukraine [2, 3].

According to the proposed methodology, the calculation of the parameters for the calibration of rolls of a continuous longitudinal rolling mill for coreless rolling (calibration or reduction) of the outer diameter of a rough pipe blank D_0 to the value D_t is carried out in the following sequence.

Calculate the total absolute deformation of the reduction along the outer diameter $\Delta D_\Sigma = D_0 - D_t$.

The number of mill stands required to perform the deformation $\Delta D_\Sigma$is determined N.

Assigning the values of the diameters of the workpiece D_i after rolling in each stand of the mill, the total absolute deformation is distributed ΔD_Σbetween the stands $N$and the partial deformations are calculated $\varepsilon_i = 1 - \frac{D_i}{D_j}$.

Specify discrete values of the broadening δb_i in the cages of the state.

Depending on the technology used to manufacture the gauges, the ovality of the gauges is determined λ_i, which provides reduction with partial deformation ε_i by widening δb_i in every cage of the state.

Depending on the gauge manufacturing technology used, the height h_i and width b_i of each gauge are calculated, as well as the gauge dimensions (radius R_i and eccentricity e_i- for each gauge that is cut individually; cutter diameter D_{fi} and cutter offset F_i - for each gauge that is cut in an assembly).

Calculations and industrial experiments. As an example, Table 1 shows the calculated parameters for rolling a D_t =168.3 mm pipe from a D_0 =182 mm billet (rolling temperature ot =740 oC) in a 5-stand calibration mill with two-roll stands, the roll calibers of which are individually cut.

Table 1 - Forming parameters when using the known (formula 1) and new improved (proposed) [3] method of calculating rolling tables of the calibration mill

Parameters	Cage number, i				
	1	2	3	4	5
Known method					
q_i	1.5	1.5	1.5	1.5	1.5
ε_i	0.02	0.03	0.01	0.0086	0
D_i, mm	178.36	173.01	171.28	169.8	169.8
λ_i	1.0307	1.0467	1.0152	1.0131	1.0000
δb_i	-0.032	0.19	0.362	0.019	
Proposed method					
δb_i, mm	0.2	0.2	0.2	0.2	
ε_i	0.02	0.03	0.01	0.0086	0
D_i, mm	178.36	173.01	171.28	169.8	169.8
λ_i	1.0438	1.0480	1.0019	1.0178	1.0000

As follows from the above data, when calculating the rolling parameters according to formula (1) for the value of the indicator 1.5 recommended in [1, Table 13] $q_i =$ (which, according to the authors, should ensure rolling with a broadening index δb_{Zi} =0.2) the values of the broadening indices are δb_i =–0.032÷0.362 and differ significantly from the value δb_{Zi} (the ratio $\frac{\delta b_i}{\delta b_{Zi}}$ varies within – 0.16…1.81). This fact is explained by the fact that when using the known method, the value δb_i is dependent on the selected values of partial deformations ε_i and the calculated values λ_i. In the case of using the proposed method (according to the method [2]), the value of the broadening index δb_i is initially set (in the example under consideration, δb_i =0.2), and the calculated values of the ovality of the gauges λ_i ensure rolling according to the initially assigned values $\varepsilon_i$and δb_i.

Industrial testing of the proposed method for calculating rolling tables (roll calibration) was performed for mills with long-roll stands and calibers cut in assembly, carried out in the conditions of a 24-stand reduction mill TPA 140, a 22-stand reduction mill TPA 30-102 and a 5-stand calibration mill TPA 350 "Interpipe Niko Tube ".

Analysis of rolling parameters when using existing roll calibrations showed that the broadening indicators δb_i in the first five stands of the reduction mill in the rolling process, they have values within δb_i =30.2÷66.2%, and in the following stands (except for the last two) δb_i =9.4÷18.4% (Fig. 1).

Considering that the 22-stand reduction mill TPA 30-102 produces both relatively thin-walled ($\frac{S_t}{D_t}$ <0.1) and relatively thick-walled ($\frac{S_t}{D_t}$ >0.1) pipes, two modes of distribution of broadening indices across the stands of the reduction mill were proposed, the parameters of which are shown in Fig. 1.

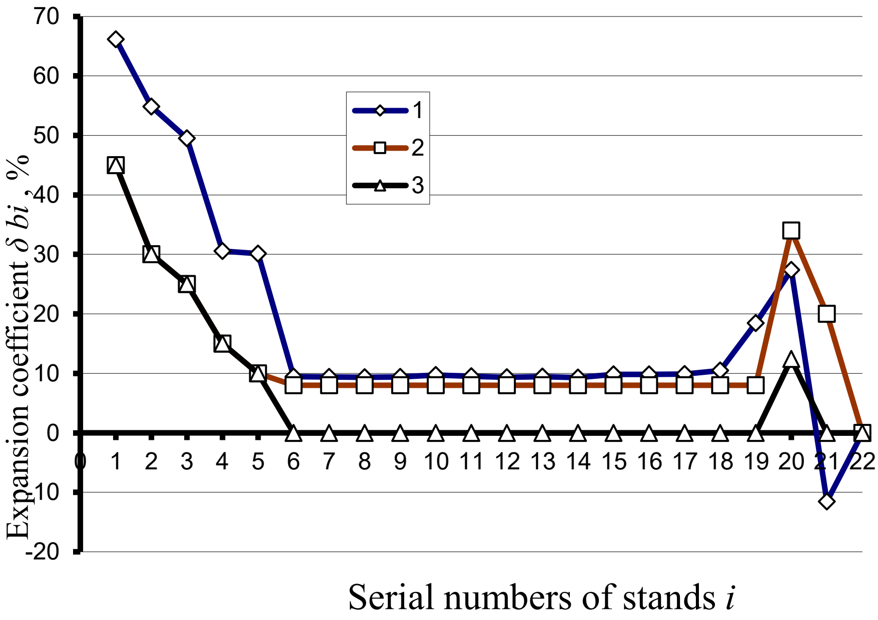


Fig. 1. Shop basic (1) and proposed (2, 3) modes of distribution of expansion indicators δb_i across the stands of the TPA 30-102 reduction mill when rolling along the "basic" route $D_0 \rightarrow D_t$ =117 →42 mm: 2 - $\frac{S_t}{D_t}$ ≤0.1; 3 - $\frac{S_t}{D_t}$ >0.1

As an example, Table 2 shows a comparison of pipe accuracy parameters when rolling pipes on a reduction mill along the route D_0x$S_0 \rightarrow D_t$xS_t= 117.0x3.50 →48.3x3.25 mm (German standard DIN 2440) using shop rolling tables and rolling tables calculated according to the proposed method [2].

Considering that on TPA 140 of JSC "Interpipe Niko Tube " only relatively thin-walled pipes ($\frac{S_t}{D_t}$ <0.1) are produced, it was decided to use one "base" calibration on the reduction mill, unlike TPA 30-102, where two "base" calibrations were introduced (see Fig. 1). For the proposed base calibration, the mode of distribution of expansion indicators was chosen δb_i on the stands of the mill, in which the value δb_i in the stands of the middle group lies within the range of δb_i=6.8…15.4% (as opposed to δb_i =10.8…19.7% for shop calibration of rolls [6, 7]. At the same time, based on the fact that preliminary ovalization of billets has a positive effect on reducing the transverse wall difference of pipes, such an arrangement of stands was proposed that provides additional ovalization (without deformation in diameter) in the stands of the main group of the reduction mill [4].

Table 2 - Comparison of accuracy parameters of pipes 48.3 x 3.25 mm according to DIN 2440 [9]

Methodology for calculating rolling parameters	Relative heterogeneity *	Ovality*	Pipe wall thickness				Outer diameter of the pipe			
			Nominal value	Actual average value	Permissible range of values		Nominal value	Actual Average Value	Permissible range values	
					according to standard	fact			According to standard	fact
	%	%	mm	mm	mm	mm	mm	mm	mm	mm
Workshop	7.9÷19.8	0.06÷0.52	3.25	3.37	1.19	1.05	48.3	48.21	0.9	0.42
Proposed	5.0÷14.3	0.04÷0.29		3.29		0.75		48.26		0.25

Notes: the table is based on the results of measurements of 30 pipes (for each position); *without the end sections of the pipe

As mentioned above, the industrial testing of the proposed modes of distribution of partial deformations and the new method of calculating the parameters of roll calibration for a 5-stand calibration mill with two-roll stands and individually cut calibers was carried out under the conditions of TPA 350.

According to the shop rolling table, it was assumed to use oval roll calibration in the first four stands, and round calibration with rounded outlets in the last stand (outlet angle $\alpha_B = \frac{\pi}{6}$rad.). The distribution of partial deformations $\varepsilon_i$across the mill stands is set in accordance with the “falling” mode ($\varepsilon_1 > \varepsilon_2 > \varepsilon_3 > \varepsilon_4 > \varepsilon_5$), and in the last stand of the mill, the partial deformation along the diameter is 0.10…1.37% [8]. For the calculation of new rolling tables and roll ε_5 =calibration parameters, it was proposed:

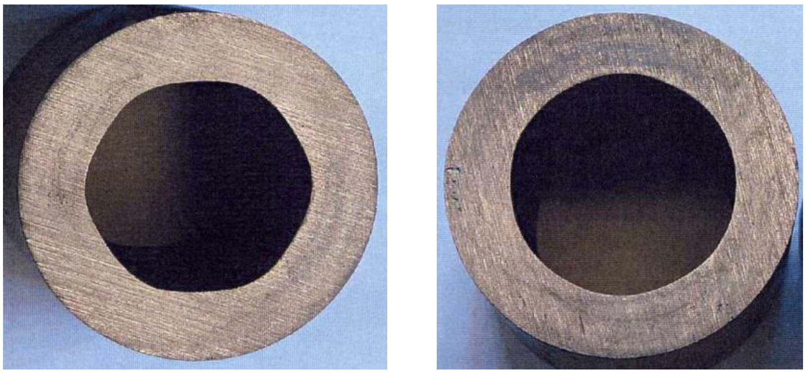
change the mode of distribution of partial deformations and choose ε_i from the condition of minimizing the calculated values of the given relative transverse heterogeneity B_t;

to reduce the ovality of finished pipes, use round roll calibration (λ_5 =0) in the last stand of the mill.

Discussion of the results. From the given data it follows that in terms of relative transverse wall unevenness and ovality, pipes that were rolled using the proposed roll calibration are more accurate than pipes rolled using shop calibration. In the given example (Table 2), the actual range of wall thickness values (absolute transverse wall unevenness ($\Delta S_t = Stmin_{tmax}$) for pipes rolled using the proposed calibration is approximately 25% less than for pipes rolled using the shop calibration of rolls (0.75 mm versus 1.05 mm, respectively); the value of M_{B_t} the mathematical expectation (average value) of the value of the relative transverse wall difference B_t pipes rolled using the proposed calibration are 1.46 times less than those rolled using the shop calibration of rolls ($M_{B_t}^{//}$ =9.6% mm versus $M_{B_t}^{/}$ =14.1%, respectively).

Summarizing the results of comparing the accuracy indicators of pipes of different sizes rolled on reduction and calibration mills using the proposed and shop calibrations of rolls, we can conclude that when using the proposed calibrations, a decrease in the relative transverse wall difference of pipes is observed B_t (the recorded values of the relative decrease M_{B_t} in the value range from 1.12 to 2.45).

It is especially worth noting the high efficiency of using the proposed method for calculating rolling tables (roll calibration parameters) of thick-walled pipes. For example, in the case of manufacturing pipes with dimensions of 57x11÷12 mm from billets of 117x9÷12 mm using the proposed rolling table, their absolute transverse wall difference is approximately 2.0÷2.5 times lower (0.8-1.0 mm versus 1.8-2.4 mm) than that of pipes rolled according to the shop rolling table (Fig. 2) [6].



a b

Fig. 2. Cross-sections of pipes D_tx S_t= 57x11 mm, rolled using the shop rolling table (a) and using the proposed rolling table (b)

The results of industrial tests became the basis for the introduction into production of new roll calibrations, the parameters of which were calculated using the proposed method.

Industrial testing of the proposed roll calibrations of the 24-cage and 22-cage reduction mills TPA 140 and TPA 30-102 of JSC "Interpipe Niko Tube " showed that the accuracy of pipes manufactured using them, in terms of relative transverse thickness variation and ovality, exceeds the accuracy of pipes manufactured using shop roll calibrations. For example, the values of relative reduction recorded during comparative experiments M_{B_t}range from $\overline{M}_{B_t}$ =1.10 to 1.45). This fact served as the basis for the industrial implementation of calibrations calculated using the proposed method in the conditions of the reduction mill TPA 140.

During rolling on a 5-stand calibration mill TPA 350 of JSC “Interpipe Niko Tube” of a pilot-industrial batch of casing pipes according to the API Spec. 5CT standard with a nominal size of 244.48x11.99 mm (blank 255x12 mm, material - steel 32G2, batch volume 1415.4 t), a decrease in the actual metal consumption coefficient by 3.4% was recorded in relation to the value that occurs in the production of pipes of the same assortment using the shop rolling table [10, 11].

The positive test results became the basis for the industrial implementation of the proposed rolling tables and roll calibrations for the entire range of pipes produced on the TPA 350.

Conclusions

A new method for calculating hot-rolled pipe rolling tables on continuous longitudinal rolling mills of various designs has been developed, which takes into account the peculiarities of the technology of cutting calibers on rolls, where the initially specified process parameter is the law of expansion distribution δb_i on the mill stands.

The proposed method for calculating rolling tables was tested in industrial conditions and implemented on the entire range of rolled pipes in the conditions of the TPA 30-102 reduction mill, the TPA 140 reduction mill and the TPA 350 calibration mill of JSC "Interpipe Niko Tube".

When using rolling tables calculated using the proposed method, the relative transverse wall difference of pipes decreases (depending on the standard sizes of rolled pipes) by 1.12…2.45 times for TPA 30-102 and by 1.10…1.45 times for TPA 140; the relative decrease in the metal consumption coefficient for TVA 350 is 3.4%.

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Концепція універсального косовалкового стана

Balakin V.F., Ugryumov D.Yu., Dobryak V.D., Ugryumov Yu.D., Nykolaienko Yu.M.

The concept of a universal cross-rolling mill

***Анотація**. Запропоновано концепцію універсального косовалкового стана (УКБ) пілігримового агрегату для вирішення його технологічних можливостей шляхом отримання гільз та товстостінних труб при прокатці на коротких та довгих оправках. Запропоновано нову конструкцію обкатного пристрою передніх кінців гільз у процесі прошивки на УКБ, що розміщується на окремій станині, що з'єднується з кліттю та напрямною проводкою. Запропонована концепція УКБ може бути використана для модернізації стана елонгатору пілігримового агрегату 5-12 ПАТ "Інтерпайп НТЗ".*
***Ключові слова:** універсальний косовалковий стан, пілігримовий агрегат, гільза, труба, обкатний пристрій, упорно-регулювальний механізм, приводні шпинделі, коротка та довга оправки, центрувальники стрижня та гільзи.*

***Abstract.** The concept of a universal oblique rolling mill (UBM) of a pilgrim unit is proposed to solve its technological capabilities by obtaining shells and thick-walled pipes when rolling on short and long mandrels. A new design of a running-in device for the front ends of shells during the piercing process on the UBM is proposed, which is placed on a separate frame connected to the cage and guide block. The proposed UBM concept can be used to modernize the elongator mill of the pilgrim unit 5-12 of PJSC "Interpipe NTZ".*
***Keywords:** universal oblique rolling mill, pilgrim unit, sleeve, pipe, running-in device, stop-adjustment mechanism, drive spindles, short and long mandrels, guide block, core and shell centering devices.*

In memory of V.M. Druyan and V.V. Perchanik (Druyan Volodymyr Mykhailovych (06/19/1932 – 04/22/2004) - famous scientist, Doctor of Technical Sciences, Professor, Head of the Department of Technological Design of the National Metallurgical Academy of Ukraine; Perchanik Viktor Volfovich (10/30/1934 – 08/04/2018) – a well-known scientist and specialist in pipe production, Ph.D. , senior researcher at the National Metallurgical Academy of Ukraine)

Introduction. The 5-12" pipe rolling unit (TPA) with pilgrim mills of PJSC "Interpipe NTZ" was put into operation in December 1968. Pipe rolling shop No. 4 with this unit was built according to the design of UkrDIPROMEZ in accordance with the technological task of VNITI.

On the 5-12" TPA with pilgrim mills, a design scheme for obtaining a sleeve is used by threading the initial billet into a cup on a hydraulic horizontal press with subsequent heating of the cup and rolling it into a sleeve with threading the bottom on a two-roll screw rolling mill - elongator [1].

With the launch of the Interpipe Steel electric steelmaking complex in 2012 and the transition of TPA 5-12” to continuously cast billets (BLZ) of round cross-section with a maximum diameter of up to 500 mm, the issue of significantly improving technical and economic indicators as a result of improving the quality of the initial billets was resolved. World experience shows that when using BLZ of round cross-section as the initial billet, the trend in technology development is to switch to direct flashing of BLZ on a slanting rolling mill. At the same time, the hydraulic press and ring heating furnace are being decommissioned. At the same time, a known technological scheme is used when part of the liner assortment is produced by direct flashing from BLZ, and a heavier liner assortment is produced according to the old scheme: preliminary flashing of BLZ into a cup with its subsequent heating and rolling into a liner on a slanting rolling mill with flashing of the bottom. In addition, when using the old Ingots cast in a mold with a wavy surface can be used for the production of sleeves.

Thus, the technological scheme with a two-stage production of a sleeve with intermediate heating is more universal in terms of the type of starting material used.

In the case of TPA 5-12” of PJSC "Interpipe NTZ", in order to use resource- and energy-saving technology when rolling the entire range of pipes by diameter (168-426 mm), it is necessary to replace the existing elongator mill with a more powerful mill, which will operate in the mode of direct threading of sleeves from a round NLS, as well as in the elongation mode when rolling out cups obtained on the press after their heating.

Elongator stand. The type of stand is two-roll with a removable cover and a cassette system for changing the feed and rolling angles. The rolls are located in a horizontal plane, and two guide rails in a vertical plane. The angle of inclination of the roll axes in a horizontal plane (rolling angle) is ±1.5°. The angle of inclination of the roll axes in a vertical plane (feed angle) is currently not adjustable and is 4°.

The existing state-of- the- art elongator is physically and morally obsolete and requires replacement, which is especially relevant in connection with the feasibility of switching to the energy-saving technology of direct threading of sleeves from a round NLS.

A feature of the hot pilgrim pipe rolling process is the presence of a seed rolling mode for the front end of the sleeve, which increases the machine rolling time and reduces productivity, and also reduces the yield of usable material due to the separation of the front end of the pipe of increased length into waste [1].

It has been established that the maximum improvement of the seeding mode of pilgrim rolling, especially of thin-walled pipes, is possible due to the preliminary preparation of the front ends of the sleeves. It is especially effective to carry out such preparation of sleeves in the process of their piercing on a cross-roll mill [2]. In pipe production, two- and three-roll piercing mills are used. At the same time, two-roll mills are the most common.

Problem statement. The current state of pipe production on pilgrim units requires finding ways to increase their loading, which is possible by expanding the technological capabilities of obtaining a wide range of pipes in the "piercing press - elongator - pilgrim mill" system when using different types of initial billets: stationary casting ingots, round-section BLZ, octagonal-section BLZ, rolled, forged and electroslag remelting.

Basic material. Let us consider the feasibility of using three-roll piercing screw rolling mills.

In works [3-6], the following advantages of three-roll piercing mills compared to two-roll equipped with rulers are noted: a more favorable scheme of the metal stress state in the deformation zone, which ensures high quality of the inner surface of the sleeves; the absence of a tool (rulers), which wears out quickly, which must be changed when changing the size and whose presence worsens the conditions for secondary gripping of the workpiece; better conditions for gripping the workpiece, a higher coefficient of axial slip and, as a result, a shorter machine piercing time; lower energy consumption; the possibility of rolling at large feed angles, which on two-roll mills is limited by the stability of the rulers.

The use of long-roll piercing mills can be considered appropriate when using cheap billets obtained by continuous casting, which are characterized by low core strength and are therefore less suitable for two-roll piercing. According to most researchers, the tendency to metal destruction when piercing by the long-roll scheme is much lower than by the two-roll one [5].

One of the disadvantages of the three-roller flashing scheme is the increased wall difference of the sleeves (compared to the two-roller flashing scheme), which places higher demands on the centering of the mandrel along the flashing axis [7].

The presence of axial looseness in round NLS should facilitate the direction of the mandrel along the axis of the workpiece.

Assel rolling mill and continuous mill is known. However, the use of long-roll piercing mills on TPA with pilgrim mills has not yet been implemented, with the exception of a piercing mill with a shifted axis (two drive rolls and one idle) on TPA 8-16" of the MDM company (Germany). Such a piercing mill occupies an intermediate position between two- and long-rolling mills in creating a stressed-deformed state in the middle of the workpiece during piercing.

The use of the technology of through-threading of the BLZ on a horizontal hydraulic press of a pilgrim unit opens up opportunities for rolling hollow billets (without a bottom) on a long mandrel in a cross-rolling mill. It is known that in foreign pilgrim units, through-threading of the BLZ into a hollow billet or cutting off the bottom of the cup is carried out. Rolling hollow billets into a sleeve on a long delivery allows you to increase the accuracy of pipes by reducing the transverse wall difference [8]. For through-hole piercing of BLZ on a horizontal hydraulic press TPA 5-12” NTZ, its modernization is necessary. The use of the technology of obtaining sleeves with preliminary piercing of ingots into a cup with a bottom on the press was appropriate only when using as the initial workpiece an open-hearth ingot cast in a mold, which has a developed shrinkage cavity in the head part. Piercing of such an ingot on the press from the bottom part led to the sinking of metal at its top, which reduced metal losses from the pilger needles that go to the edge.

Through-hole insertion of the BLZ on the press of the pilgrim unit also allows for quick control of the transverse wall difference of the rear part of the hollow workpiece for press adjustment.

Problem statement. It is necessary to propose a concept of a universal cross-rolling mill for the modernization of the 5-12” NTZ pilgrim mill by replacing the existing cross-rolling mill- elongator.

The new cross-rolling mill should be universal for performing the following operations:

- threading of a round cross-section BLZ into a sleeve on a short conical mandrel; to improve the quality of the inner surface of the sleeve, the mill stand must be long-rolled;
- elongation (rolling) of glasses obtained on a press with intermediate heating in a ring furnace;
- preparation of the front ends of the sleeves in the process of flashing (rolling) taking into account the existing experience of operating the running-in device on the TPA 5-12” NTZ elongator mill [2];
- rolling of hollow blanks on a long mandrel after through-hole piercing of the BLZ on a horizontal hydraulic press with intermediate heating of a ring furnace.

It is known that obtaining liners with pre-threading of ingots on a press expands technological capabilities by using various types of starting blanks: stationary casting ingots, round and octagonal BLZ, electroslag remelting ingots, centrifugally cast billets, hollow BLZ, etc. The use of a universal slanting rolling mill of a pilgrim unit increases these capabilities, and also allows switching to an energy-saving technology for obtaining liners in the absence of additional heating of the metal before rolling on a slanting rolling mill.

The preparation of the front ends of the sleeves on a cross-roller mill during the process of threading (elongation) is proposed to be carried out using a new technology, which consists in reducing the front end of the sleeve without compression along the wall, which eliminates the use of a cylindrical mandrel. The size of the reduction along the outer diameter is up to 20 mm. At the same time, the inner diameter of the sleeve at the front end is reduced (the change in wall thickness is not taken into account). This contributes to the centering of the front end of the sleeve on the mandrel after it is loaded. The new technology for preparing the front ends of the sleeves together with the centering of the rear end of the sleeve on the conical shank of the mandrel ensures a reduction in the transverse wall difference of the pipes during pilgrim rolling and reduces the metal consumption factor.

In the 1980s, for the modernization of the 5-12" TPA with pilgrim mills of PJSC "Interpipe NTZ" with the replacement of the existing two-roll elongator with guide rails, the concept of a three-roll stitching mill with a universal running-in device has been proposed [9-11].

The project was implemented by employees of the Dnipropetrovsk Metallurgical Institute: V.M. Druyan, V.V. Perchanik, O.M. Komarov, VNDTI: O.A. Plyatskovsky, Y.G. Pavlovsky with the participation of UkrDipromez, NTZ and Chepel Metallurgical Plant.

The general view of a three-roll stitching mill is shown in Figure 1.

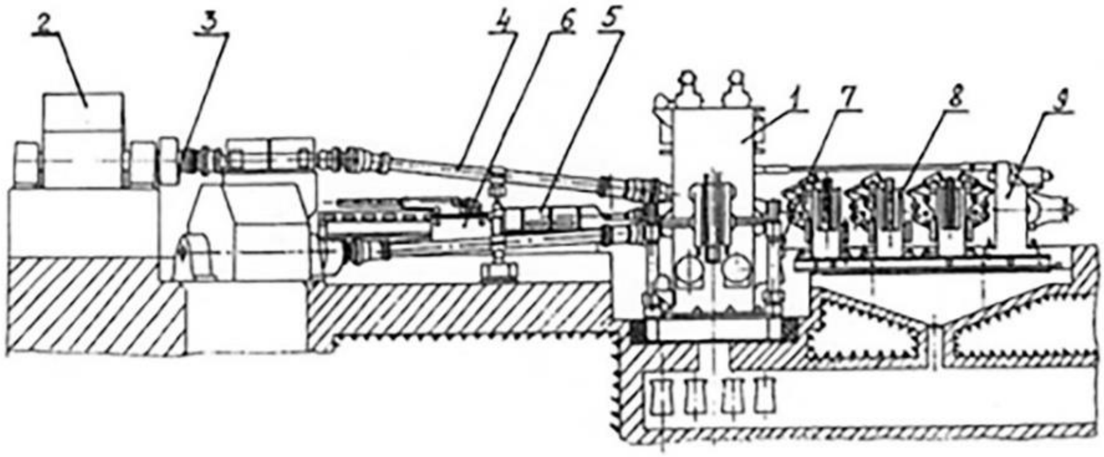


Figure 1 – Scheme of a three-roll piercing mill [9]: 1 - piercing mill stand; 2 – drive electric motor; 3 – coupling; 4 – universal spindle; 5 – receiving chute; 6 – workpiece pusher ; 7 – idle rolls for running in the sleeve end; 8 – rod centering devices ; 9 - thrust -adjusting mechanism

The technical characteristics of the long-roll stitching mill are given in [10].

The previously proposed concept of a long-roll stitching mill [9-10] is taken in this work as a basis for developing the basic provisions of the UKS design, while taking into account new tasks, the concept of the known mill is subject to certain changes and additions.

The purpose of this work is to expand the technological capabilities of the cross-roller mill as part of the 5-12" pilgrim unit and select a rational type of this mill for various technological schemes for producing sleeves.

Universal cross-rolling mill for modernization of the pilgrim unit.

Working stand. Working stand 1 contains a frame, working drive rolls with bearings, a pressure and balancing device for the rolls (see Fig. 1).

Each working roll of the mill receives rotation from the electric motor 2 through the coupling 3 and universal spindles 4. The spindle of the upper roll is connected to the coupling 3 through a horizontal intermediate shaft. To unload the spindle hinges in the geometric center of each, a support with hydraulic balancing and spring shock absorbers of dynamic loads is installed. To receive the workpieces and direct them to the mill rolls, a receiving chute 5 is installed between the spindles, the height of which is adjusted using spacers. To set the workpiece into the rolls, a hydraulic pusher 6 is installed.

Three working rolls are placed in the frame at an angle of 120° to each other (with one roll positioned at the top and the other two at the bottom), and three idle rolls 7 are installed at the rear end of the frame for running in the front end of the sleeve, offset by 60° relative to the working rolls.

The input side of the mill contains three electric drive motors for individual drive of the work rolls, clutches, universal and intermediate spindles, a receiving chute and a billet pusher .

Figure 2 shows a diagram of the input side of the mill with three main spindles 1, 2 and 3 and one intermediate spindle 4 and three drive electric motors 5, 6 and 7. The permissible skew angle of the spindles is no more than 8°.

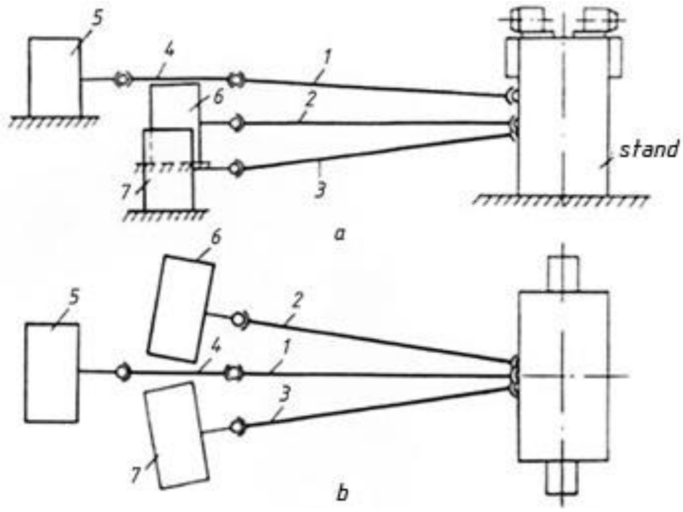


Figure 2 – Scheme of the input side of the mill: a – main view; b – top view; 1-3 – main universal spindles; 4 – intermediate horizontal spindle; 5-7 – drive electric motors

Drive spindles of the working rolls of the mill [11]. The use of ball spindles on a long-roll mill will ensure reliable centering, reduce spindle runout, reduce vibrations of the working line and inertial forces. This project is one of the design options for the drive of the working rolls of a long-roll mill, which provides the transmission of torque with minimal unevenness of angular velocity during one revolution.

Guide wire. It is installed directly near the mill rolls. One of the main provisions for reducing eccentricity during oblique roll threading is to ensure that the axes of the workpiece, threading, and sleeve coincide.

Therefore, a guide (input) wire is installed on the input side of the mill, the axis of the working channel of which must coincide with the axes of the firmware and the sleeve at the exit from the rolls.

The guide wire operates in quite difficult conditions: hot metal, dynamic impacts when the workpiece rotates with the rolls. The length of the guide part of the wire is important, which should be slightly less than the minimum length in the workpiece assortment. For example, with a minimum workpiece length of 1200 mm, the wire length can be 800-900 mm. Usually the gap between the workpiece and the working channel of the wire is 20 mm. However, it is necessary to strive to reduce this gap to 10-12 mm, while the wire should not interfere with the free movement of the workpiece in the mill rolls. It is also necessary to take into account the curvature of the workpiece and fluctuations in its diameter.

As noted by the company "SMS MEER" (Germany), pipe eccentricity is the main problem in the production of seamless pipes. This problem is mainly associated with failures in the operation of the cross-roller piercing mill. In conditions of high competition among pipe manufacturers, the requirement for product quality can only be met by limiting the eccentricity. The size of the eccentricity of seamless pipes (from 8% and above) is almost twice as large as the deviation in the wall thickness of pipes manufactured on highly automated multi-cell and reduction -stretching mills. Reducing the eccentricity by 1% provides cost savings of 1% of the annual production volume (in tons).

On a number of slant-roll piercing mills of the company "SMS MEER" a certain reduction of eccentricity has been achieved due to the new design of the inlet section. Figure 3 shows the guide wiring at the inlet of the rolling mill, which illustrates the possibility of precise direction of the rolled material to the work rolls. This block is successfully used on several rolling mills. The main element of this block is a guide sleeve of a rather significant length (as follows from Fig. 3), which changes when the diameter of the initial workpiece changes. The sleeve is fixed in the block by means of bolted connections.

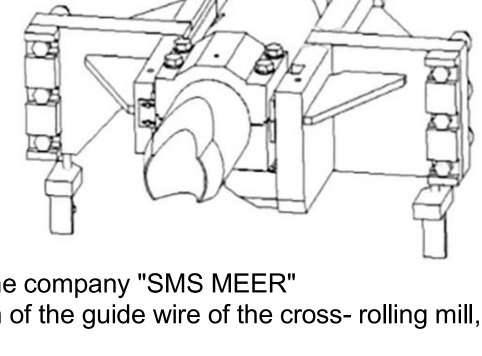


Figure 3 – Directional wiring of the company "SMS MEER"

We have proposed a new design of the guide wire of the cross- rolling mill, which is shown in Figure 4.

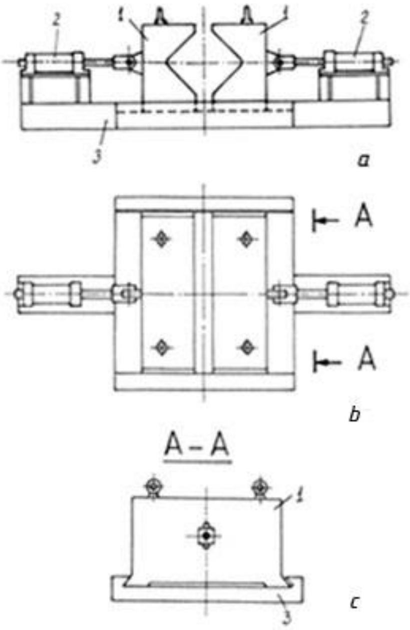


Figure 4 – Guide wire of a cross- rolling mill: a – general view; b – top view; c – section A-A in Fig. 1b; 1 – figured slider; 2 – hydraulic drive; 3 – frame base

On the frame base are two figured sliders that move perpendicularly to the mill axis using hydraulic cylinders. In cross-section, the sliders in the working position form an internal channel (of a square profile) for the passage of the initial workpiece of a round cross-section. The channel formed by the sliders 1 serves to direct the workpiece into the mill rolls along the insertion axis. This shape of the figured sliders 1 ensures centering of several standard sizes of workpieces in diameter due to the expansion-contraction of the sliders 1, which must move synchronously to stabilize the workpiece axis relative to the insertion axis (Fig. 5).

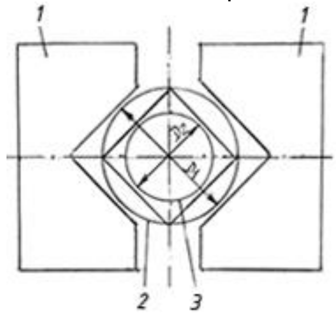


Figure 5 – Scheme of centering a workpiece of circular cross-section with diameters D1 and D2 using figured sliders: 1 – figured sliders; 2 – workpiece with diameter D1; 3 – workpiece with diameter D2

To reduce the eccentricity of the front ends of the sleeves, it is necessary to accurately center the front end of the workpiece with the formation of a hole of the required diameter and depth of the corresponding mandrel toe.

The output side of the mill. Contains a device for running in the front ends of the sleeves during the insertion process, a centering and transporting device; a thrust -adjusting mechanism (RUM), etc.

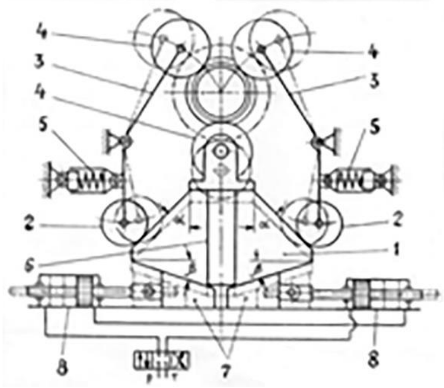
Device for running-in of the front ends of sleeves. In work [10] it was proposed to place a universal device for running-in (sharpening) of the front ends of sleeves on the input side of the long-roller piercing mill, which, in our opinion, is complex and, as a result, insufficiently reliable (see Fig. 1).

We propose a new design of a device for running-in (sharpening) the front ends of sleeves during the flashing process, working in tandem with the UKS cage, devoid of the above-mentioned disadvantages.

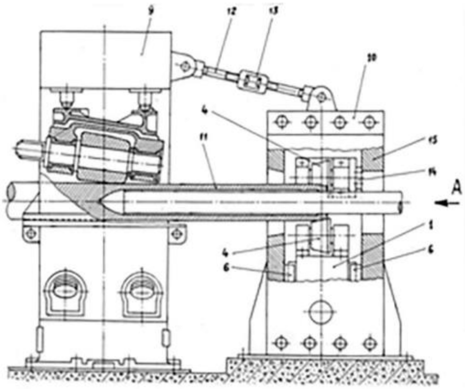
The kinematic diagram of the new device at the moment of the end of the sleeve sharpening is shown in Fig. 6a.

The device is a combination of two pairs of simple mechanisms: a cam-lever and a wedge-lever. The cam -lever mechanism consists of a cam 1, which contacts two symmetrically arranged rollers 2, hingedly mounted on the lower ends of two double-arm levers 3. Deforming non-driven rollers 4 of conical shape are hingedly mounted on the upper ends of the levers 3. The third deforming roller 4 is hingedly mounted on the upper platform of the cam 1. The αcam inclination angles are chosen such that when the cam is moved from the upper position to the lower position, the deforming rollers 4, mounted on the upper ends of the levers 3, move synchronously from the small contact circle to the larger contact circle. The small contact circle corresponds to a small diameter sleeve, and the large contact circle corresponds to a large diameter sleeve. Since the segments connecting the center of the sleeve with the centers of rotation of the rollers 4 always converge at one fixed point, namely at the center of the sleeve, such a device performs an additional self-centering function. The force locking of the cam 1 and the rollers 2 is carried out by means of compression springs 5, which constantly press the rollers 2 to the cam 1.

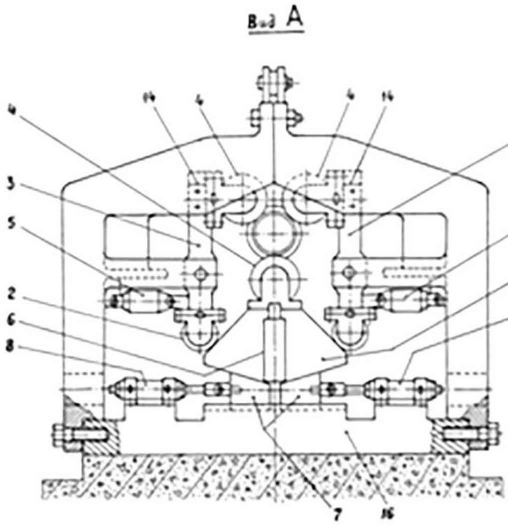
The vertical movement of the cam 1 in the guides 6 is carried out using wedges 7, which must be, on the one hand, large enough so that the stroke of the wedges for raising and lowering the cam is small, and on the other hand, not too small so that there is no jamming. We recommend an angle of β=15°. The wedges must converge or diverge synchronously. This is achieved by the fact that each hydraulic cylinder 8, in addition to the working rod, has a false rod, and the connection of the pipelines must be made as shown in Figure 6a. Since the deforming rollers 4 after sharpening the sleeve must quickly move away from it, the time of rapid action of the hydraulic cylinders 8 must be minimal, which is achieved by minimizing the working volume of the rod cavities of the hydraulic cylinders. For this, the diameter of the hydraulic cylinders must be minimal, and the diameter of the rods maximum, of course, while ensuring a given force on the working rod.



A



b



c

Figure 6 - Stand of a long-roll mill and a device for sharpening a sleeve: a - kinematic diagram of a device for sharpening a sleeve; b - main side view; c - view from the arrow in Fig. 6b; 1 - cam; 2 - roller; 3 - lever; 4 - deforming roller; 5 - compression spring; 6 - guide; 7 - wedge; 8 - hydraulic cylinder; 9 - piercing mill; 10 - device for sharpening a sleeve; 11 - sleeve; 12 - tie; 13 - tie nut; 14 - support plate; 15 – housing

Figure 6b shows a sketch of the UKS 9 in tandem with the device 10 for sharpening the sleeve 11. The moment of the end of sharpening and the beginning of the departure of the deforming rollers 4 from the sleeve is shown. The distance between the axes of the mill 9 and the device 10 should be selected from the condition of preventing the loss of longitudinal stability of the sleeve from the resistance force of the device and taking into account the necessary space for servicing both the UKS and the running-in device. The force closure between the mill 9 and the device 10 is carried out using a tie 12 with a tie nut 13. Fig. 6b shows the deforming rollers 4, the cam 1, and the cam guides 6. To relieve the levers 3 from bending, support plates 14 are fixed to them, which transfer the load to the housing 15. The plates are made of textolite. The lower deforming roller 4 of the device 10 transmits the force from the sleeve 11 to the rear guide 6 of the cam and then to the housing.

Figure 6c shows a view from arrow A in Figure 6b (conditionally without the rear wall of the housing), from which it can be seen that the housing consists of at least two parts, resting at the bottom on the base 16, fixed to the foundation, and connected at the top with bolts. On the base 16, guide grooves for wedges 7 and seats for the hydraulic cylinder 8 are made.

It is advisable to equip the output side of a long-roller UKS for sleeve insertion as follows:

- after the mill stand, a running-in device is installed, and between them the first centering device for the mandrel rod and the sleeve;
- immediately after the stop -adjustment mechanism, a second rod centering device is installed, which performs the rod centering operation before insertion [10];
- it is possible to install a third centering device between the running-in device and the second centering device;
- after the running-in device, a ramming device is installed, which ensures that the sleeve exits the zone of action of the running-in device when the lock is closed;
- the required number of oscillating rollers with individual drives are installed between the centering devices, which perform the operations of holding the sleeve with the rod along the axis of the insertion and transporting it after the running-in device fixes the position of the rod and the lock opens;
- for rolling blanks on a long mandrel, appropriate equipment is installed, including for holding the long mandrel during the rolling process.

Thrust -adjusting mechanism (TAM). In the proposed concept of the mill, the TAM corresponds to modern trends in influencing the geometric parameters of rolled sleeves by moving the mandrel during the flashing process [12], which allows obtaining a sleeve at the rear end with an increased inner diameter. This solves the problem of loading the mandrel into the sleeve with minimal gaps between them, as well as removing the sleeve from the rod after flashing with rolling its front end.

Technological schemes of rolling on short and long mandrels. In work [13], a universal cross-rolling mill (UKM) for rolling on short and long mandrels is proposed.

This mill provides rolling according to the following technological schemes: rolling of sleeves on a long floating mandrel; rolling of sleeves with support; rolling of sleeves with tension; rolling of sleeves on a held, partially held and mandrel that is pulled out during the rolling process; piercing of blanks on a short mandrel and rolling of sleeves on a short mandrel.

The individual technical solutions presented in [13] can be used to design a new UCS as part of a pilgrim unit.

For rolling on a UKS using short and long mandrels, it is necessary to provide for operations for cooling and lubricating these mandrels. The installation [14] can be taken as the basic option for solving this problem.

The operations of cooling and lubricating the mandrels are conveniently carried out on a special installation with lateral delivery of sleeves from the UKS.

As a result of the flashing with the preparation of the front end of the sleeve before pilgrim rolling, it will have the appearance shown in Figure 7.

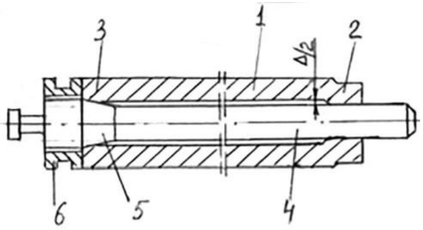


Figure 7 – Position of the sleeve with the prepared front end on the mandrel before pilgrim rolling: 1 – main part of the sleeve; 2 – prepared front end; 3 – rear end of the sleeve; 4 – main part of the mandrel; 5 – conical shank of the mandrel; 6 – mandrel ring (Δ- gap between the sleeve and the mandrel)

The use of a mandrel with a tapered shank and a sleeve with a prepared front end ensures centering of the sleeve on the mandrel before pilgrim rolling, which reduces the difference in pipes and increases the yield.

Conclusions

The concept of a long-roll UKS for the reconstruction of TPA 5-12” with pilgrim mills of PJSC “Interpipe NTZ” is proposed, which allows for threading of round-section NLS into a sleeve, rolling of cups with threading of the bottom, and rolling of hollow blanks on a long mandrel.

The main features of the proposed mill are individual drive of the work rolls; the presence on the output side of the mill's working stand of a new device for running in the front ends of the sleeves; the use of a URM to move the rod with the mandrel during the piercing process; the use of centering devices for the mandrel rod and sleeve, the use of short and long mandrels, and a new design of the guide wire.

The proposed design of the running-in device, placed on a separate frame, will ensure increased reliability of its operation and improved maintenance conditions for the UCS and the running-in device.

It is advisable to further consider the possibility of using a transformed UKS oblique roll stand for working with two and three rolls to produce thinner-walled pipes.

unevenness of the pipes and an increase in the yield during the pilgrim rolling process.

The proposed concept of the UKS can be used to develop a technical task for the design of a new cross-rolling mill to replace the existing elongator mill. pilgrim unit 5-12” NTZ.

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Удосконалення гарячої пілігримової прокатки труб

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Improvement of hot pilgrim pipe rolling

Аннотація. *Розглянуто основні методи поліпшення затравочного режиму з урахуванням відношення D/S труб, що прокатуються. Запропоновано здійснювати прокатку труб у затравочному режимі зі змінною величиною подачі по заданій програмі, а також нові рішення з прокатки гільз встик. Розглянуто два нових напрямки підготовки передніх кінців гільз на чотирьохбойковому гідравлічному пресі та на обкатній машині планетарного типу. Запропоновані нові методи підготовки задніх кінців гільз за рахунок потоншення стінки на задньому кінці гільзи в процесі прошивання заготовки на косовалковому стані за рахунок переміщення оправки, а також – обтиснення заднього кінця гільзи на дорні на двобойковому гідравлічному пресі. Запропоновано комбіноване використання розглянутих методів поліпшення затравочного режиму, що підвищить продуктивність і зменшить витрати металу в обріз.*
Ключові слова: *пілігримова прокатка, пілігримовий стан, труба, гільза, несталий затравочний режим, подавальний апарат, дорн, подача, коефіцієнт витяжки, валки, витратний коефіцієнт металу, підготовка передніх і задніх кінців гільз, продуктивність.*

Abstract. *The main methods of improving the feeding mode taking into account the D/S ratio of rolled pipes are considered. It is proposed to carry out rolling of pipes in the with variable feed rate according to a given program, as well as new solutions for butt shell rolling. Two new directions for the preparation of the front ends of the sleeve liners on a four-row hydraulic press and on a planetary type reeling machine are considered. New methods of preparing the rear ends of the sleeves by thinning the wall at the rear end of the sleeve in the process of piercing the workpiece on the rotary piercer mill by moving the mandrel, as well as by crimping the rear end of the sleeve on the mandrel on a two-punch hydraulic press. The combined use of the considered methods of improving the inoculation mode is proposed, which will increase productivity and reduce metal consumption in the cut.*
Keywords: *pilgrim rolling, pilgrim mill, pipe, sleeve, unsteady inoculation mode, feeder, mandrel, feed, draw ratio, rolls, metal consumption ratio, preparation of the front and rear ends of sleeves, productivity.*

To the 90th anniversary of the birth of V.V. Perchanik (Perchanik Viktor Volfovich (10/30/1934 – 08/04/2018) – a well-known scientist and specialist in pipe production, Ph.D., senior researcher at the National Metallurgical Academy of Ukraine)

Introduction. The hot pilgrim pipe rolling process is used worldwide for the production of oil and gas, oil pipeline, boiler, and special purpose pipes of a wide range of sizes and grades. Currently, about 40 pilgrim units are in operation worldwide. In Ukraine, a 5-12" TPA is currently operating at the Nizhnyodneprovsk Pipe Rolling Plant (NTZ). The hot pilgrim pipe rolling process has the following advantages: the possibility of producing pipes of considerable length, as well as thick-walled ones, which cannot be obtained by other methods, except for pressing; the possibility of significantly improving the structure of the initial cast material due to significant total deformations on the pilgrim mill; a short duration of transition to another pipe size; the possibility of using a continuously cast round billet as an inexpensive initial material with a diameter of up to 500 mm; the feasibility of producing small-tonnage batches of pipes. From the analysis of the main performance indicators of various TPAs, it follows that the production of pipes on pilgrim units has higher metal consumption factors (MCF) by 100-150 kg per ton compared to other units, which is due to inevitable technological losses of metal on the seed and the pilger head. The value of MCF during the rolling of thick-walled and especially thick-walled pipes can be compared with VKM on other units due to the use of metal-saving technology of rolling sleeves end -to-end onto mandrels with rolls, which minimizes the final cut of pipes.

Features of the hot pilgrim pipe rolling process: The hot pilgrim pipe rolling process is characterized by the presence of steady-state and non-steady-state processes, which include the seeding mode and the finishing mode. pilgrim head. Unsteady processes are characterized by the instability of such pilgrim rolling parameters as feed, rollback, canting angle, compression by diameter and wall thickness, and draw ratio [1-4]. Unsteady seeding mode is the most difficult rolling mode due to the instability of the conditions of metal capture by the rolls, increased transverse flow of metal in the roll caliber outlet. In this case, there is an increase in the cut of the front defective ends of the pipes, as well as a decrease in the mill productivity due to the duration of the seeding mode, which is 5-15% of the machine rolling time. Difficult conditions of the seeding mode are due to significant draws (up to 15) and deformations of pipes with a front support from the side of the feeder. Metal losses in the seeding front end of the pipe reach a length of 500-700 mm or more and increase with increasing draw. The greatest metal losses occur during the rolling of thin-walled pipes with a ratio of D/S=12.5-40.0 and especially thin-walled pipes with D/S> 40 - the main assortment of TPA 5-12" NTZ. A feature of the process of hot pilgrim rolling of pipes is the presence of a pilgrim head at the rear end of the roll, which is due to the stop of the rear end of the sleeve in the mandrel ring, as a result of which rolling occurs with a constant front support on the sleeve from the side of the feeding apparatus. The formed undercut of the rear end of the sleeve is called the pilgrim head and goes into the cut, increasing the metal consumption coefficient.

Features of the seeding mode of pilgrim rolling [1-4]: during seeding The pilger mill does not produce a finished pipe, but forms a pilger head on the sleeve; metal waste during cutting the seed end of the pipe reaches 30% of the total technological cutting on the pilger mill; the conditions for gripping the sleeve by the rolls are complicated, since the metal meets the roll before the line of the roll centers; the impact of the roll crest on the metal causes increased dynamic loads in the working line of the mill; there is no synchronization (especially in the initial period of seeding) of the operation of the feeding apparatus with the rotation of the working rolls due to the variable length of the rollback and the undercutting of the sleeve; the high-speed rolling mode is limited by the conditions of the sleeve's adhesion to the mandrel and inertial forces at the moment of braking of the feeding apparatus; the feed amount is limited by the uneven deformation along the perimeter of the sleeve in the absence of a rigid front end of the pipe; increased wall unevenness in the seed area and further in some part of the finished pipe for the same reasons.

After the start of deformation of the sleeve on the mandrel by the rolls in the seeding mode, the feed rate is important, which is determined by the movement of the sleeve in the rolls in each cycle. In practice, they strive to carry out the seeding mode of pilgrim rolling with small feeds, since it is not controlled and a situation of mill overload due to a large feed is possible. In practice, the feed rate during the seeding mode does not exceed the feed rate in the steady mode. This prolongs the seeding process and increases the machine time of rolling with a corresponding decrease in the productivity of the mill. The process of the seeding mode of pilgrim rolling is influenced by the capabilities of the applied feeders. The unmodernized feeders operated in Ukraine significantly complicate the seeding process, especially during the rolling of thin-walled pipes. Thus, improving the seeding conditions, their maximum possible approximation to the steady process is an important reserve in increasing productivity and improving the technological performance of pilgrim units.

Problem statement. The unstable seeding mode of pilgrim rolling reduces productivity and increases metal consumption in the final cut. Given the complexity of the problem, it has received only a partial solution mainly for rolling thick-walled D/S= 6.0-12.5 and especially thick -walled D/S<6 pipes. The current work is devoted to the development of new technological solutions for improving the seeding mode when obtaining both thick-walled and thin-walled D/S= 12.5-40.0 and especially thin-walled D/S>40 pipes.

The main part

A.O. Chernyavsky proposed dividing the seeding process into two separate stages [1]. The first stage of seeding is characterized by the meeting of the sleeve with the rolls in front of the line of their centers (Fig. 1a). Due to the fact that the rolls are ahead of the sleeve, friction forces arise in the contact area formed as a result of the initial interaction of the sleeve with the rolls, directed in the direction of rotation of the rolls. The first period of seeding lasts until the preliminary seeding end is formed, which makes it possible to feed the sleeve beyond the line of the centers of the rolls without the risk of excessive overloading of the mill due to a sudden increase in the feed. During this period, not rolling takes place, but forging of the sleeve, which is periodically fed into the rolls.

At the second stage of seeding, the sleeve with the previous seed end is set behind the line of the centers of the rolls and a portion of the metal is squeezed out by the rolls with its subsequent rolling (Fig. 1b). If at the first stage the support contributed to the implementation of the seed, then at the second stage its value decreases, and in practice during the second stage the force Q_n reduced by bleeding air from the acceleration chamber of the feeder. This helps reduce transverse deformation of the metal in the caliber, which reduces the duration of forming the seed end and improves its quality.

The size of the cut of the seed end of the pipe is influenced by many factors, the main of which are: the size of the pipes being rolled (diameter and wall thickness); the quality of the starting metal of the billet; the steel grade and the temperature regime of rolling; the design of the feeding apparatus; the feeding regime during seeding; the extraction coefficient during seeding; the gap between the mandrel and the sleeve, etc. [5, 6]. The cut of the seed end conventionally consists of two parts. The first part is due to significant unevenness of the deformation along the rolling perimeter, and the second - to increased pipe wall heterogeneity. Significant unevenness of the deformation along the rolling perimeter occurs due to the absence of a rigid front end of the pipe during seeding, which leads to the pulling of individual portions of metal along the side walls of the caliber independently of each other and, accordingly, to the violation of the continuity of the metal. The reason for the increased pipe wall difference is the presence of a gap between the sleeve and the mandrel, which, due to the uneven deformation of the sleeve along the perimeter, leads to asymmetric clamping of the sleeve on the mandrel by the rolls. In the general technological cut on the pilger mill seeding is 23-30%, and in some cases more. The duration of seeding is subject to the influence of many factors that act with different intensity in different conditions. Moreover, these factors are partly subjective and random in nature. Rolling of thick-walled pipes (D/S<10) requires no more than two roll strokes for seeding. The performed analysis of the features of the seeding mode allows us to consider the main methods of its improvement from new positions, taking into account both previously performed works [1-4] and recent publications [5, 6].

The main methods for improving the seeding mode: reducing the draw ratio on the pilger mill; increasing the adhesion of the sleeve to the mandrel before rolling; using special rings; rolling the sleeves end-to- end; forcing the sleeve to be tilted by 90° during seeding; choosing a rational feed mode during seeding; choosing a high-speed rolling mode; preliminary preparation of the front (rear) ends of the sleeves.

1. Reducing the draw ratio on the pilger mill. This method is widely used in practice when rolling thin-walled and especially thin-walled pipes (with a pipe wall thickness on the pilger mill S=5-7 mm). When the rolls make 8-10 revolutions from the beginning of the seed, the upper roll is smoothly lowered. Under the existing conditions, only this method makes it possible to roll pipes with S=5-7 mm. The existing thickening of the pipe wall during the lifting of the upper roll is then removed into the cut along with the defective end, which increases the mass of the total cut. In order to increase the yield, in the work [7] it is proposed to deform the front end of the sleeve during the separation of the rolls of the pilger mill by 1.02-1.15 times greater than the separation of the rolls set during the rolling of the middle part of the sleeve. After that, the separation of the rolls is set in accordance with the rolling mode of the middle part of the sleeve and deform it from beginning to end. To reduce the technological cut on the pilger mill, a combined technology for rolling thin-walled pipes on a pilgrim installation is proposed, which includes a slanting roll rolling mill with a short mandrel. The essence of the new technology is that on the pilger mill the front and rear ends of the pipe, corresponding to the seed and the pilger head, are rolled with an increased wall thickness, subsequently the wall thickness is equalized along the length of the pipe on the rolling mill [1]. The wall thickening at the ends (compared to its middle part) should not exceed the maximum value of the wall crimp on the rolling mill.

2. Increasing the sleeve-mandrel adhesion before rolling. Increasing the sleeve-mandrel adhesion allows you to intensify the pilgering process, especially at the initial moment of rolling in the seeding mode. This method allows you to choose a more optimal rolling speed mode along the length of the pipe. The gap between the sleeve and the mandrel during seeding increases the flattening of the roll due to reduction, and this prevents canting. In addition, the presence of a gap between the sleeve and the mandrel during the seeding period leads to an increase in the unevenness of deformation across the caliber width and, as a result, to the appearance of cracks and additional cutting of the front end of the pipe. Reducing the gap to the minimum required values (10-12 mm), which ensure stable loading of the mandrel into the sleeve, is in practice carried out by improving the quality of the sleeve piercing on the cross- rolling mill. To ensure a minimum gap between the mandrel and the sleeve, the latter must have minimal curvature and a stable (within the permissible limits) inner diameter along the length of the sleeve, which is achieved mainly by the correct setting of the cross-rolling mill.

Thus, to reduce the final cut during seeding, it is necessary to strive to reduce the gap between the sleeve and the mandrel along the entire length of the sleeve or at its front end. On the 6-12" NT3 TPA, it was found that reducing the gap Δbetween the sleeve and the mandrel leads to a reduction in seeding duration by 11.6-18.2%, other things being equal [8].

3. Use of special rings. This method has been used during the rolling of pipes from high-alloy and special steels and consists in the use of additional rings from carbon steel, which are put on the mandrel and joined to the front end of the sleeve. As a result of rolling into the edge, the defective end from carbon steel is removed, which makes it possible to significantly reduce the consumption of alloyed and special steels. The most widespread method is welding a special ring to a hollow workpiece with subsequent heating to the deformation temperature and rolling directly on a pilger mill. It is possible to join a heated special ring and a hollow workpiece on a mandrel and compress the ring on a press to increase adhesion.

4. Butt-rolling of sleeves. The method has found wide application during rolling of thick-walled pipes with D/S=6-12.5 and especially thick-walled pipes with D/S<6 [1]. It provides reduction of the cutting of the front and rear ends of the pipes due to a more uniform distribution of deformation over the width of the caliber due to the presence of "hard ends". For rolling of pipes with thinner walls it was proposed to reduce the section of the sleeve joint before the main deformation along the wall thickness (Fig. 1). In this case, the draw ratio during reduction of the sleeve wall is μ_1 =1.03-1.15, and the elongation coefficient during deformation along the wall μ_2 = 4-9 [9]. The second option for implementing the technological capabilities of the butt-rolling method of sleeves is the use of carbon steel rings between the sleeves joined by mandrels (Fig. 2).

5. Forced tilting of sleeves by 90° during seeding. In conventional air cylinders of a forgoler, the rotation of the sleeve by an angle of 90-120 degrees is carried out using a drill. Part of the plunger is made with a thread that works in conjunction with a nut. The nut engages with the threaded part of the plunger during its movement towards the rollers. The angle of rotation depends on the size of the plunger stroke and is not a constant value. In the air cylinder of the company " Mannesmann-Demag " (Germany), in addition to the drill, a device for forced tilting of the sleeve is provided. The optimal tilting angle is set, which is 90 degrees. In this case, the drill is made in such a way that the tilting always occurs at an angle less than 90 degrees, and the forced tilting device turns the sleeve to 90+(5-10) degrees. [10]. The forced canting device is also designed to reduce the number of seed blows, which is currently 11-12, and sometimes increases to 18. This is due to the lack of canting in the initial rolling period.

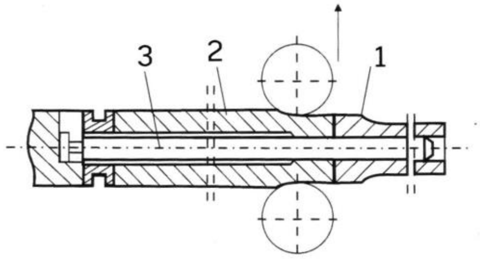

Fig. 1. Stage of reducing the joint of the sleeves: 1 and 2 - the previous and next sleeves, respectively, 3 - mandrel

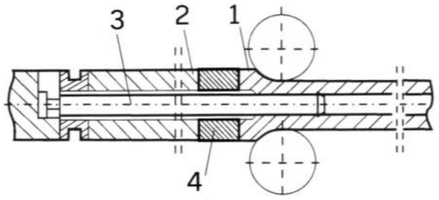

Fig. 2. Rolling of sleeves end-to-end with a ring between them: 1 and 2 - previous and next sleeves respectively, 3 - mandrel, 4 – ring

6. Choosing a rational feed mode during seeding. In practice, it is known to use two feed modes during seeding. The difference between them is that the first mode is carried out at a feed equal to its value in a steady state. The second feed mode is characterized by the fact that at the beginning of the seeding process (in its first cycles) the feed value significantly (2.5-3 times) exceeds its value in a steady state. This feed mode is used in practice more often, since it allows you to reduce the duration of the unstable seeding mode by 50-70% compared to the first mode, which, in turn, provides a reduction in the final cut due to less uneven deformation of the metal in the caliber, which makes it possible to use it during the rolling of special (expensive) steels.

There are known proposals for improving the feed mode during seeding, and according to the first of them, the next volume of metal is fed when a signal is received about the complete rolling of the previous metal feed, which should contribute to reducing the unevenness of metal deformation in the caliber, and should also make the automation of the seeding mode more realistic. According to the second proposal, it is recommended that the metal feed into the rolls during seeding (as well as during the rolling of the entire sleeve) be carried out according to a pre- set program, which will allow you to more rationally choose the required feed mode and quickly change it [2].

To achieve the exact optimal feed rate, mechanisms are provided that combine the hydraulic drive of the carriage movement with a mechanical device for precise dosing of the amount of this movement [10]. During the seeding of the sleeve into the rolls, the nut of the feed dispenser moves according to a given program. The carriage of the feeding device is pressed against the nut, which thus determines the feed rate. Later, during a stable process, the nut moves by a constant value *m* with a frequency corresponding to the frequency of rotation of the pilger mill rolls. This ensures the exact volume of metal that is given into the rolls.

Currently, during seeding, feed mode 1 is used, when the feed $m$is equal to the feed my in the steady rolling mode (Fig. 3), which increases the seeding duration to approximately 20 s. In the case of using a sleeve with a prepared front end and in the presence of a feeding device with a mechanical feed dispenser, a variable feed mode 2 can be implemented, which reduces the seeding duration to 10 s. The third feed mode is used for rolling heavily deformed steel grades.

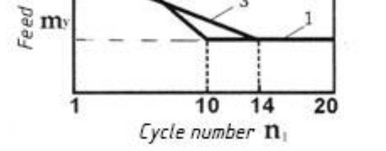

Fig. 3. Feed modes 1, 2 and 3 *m* during casing priming

7. Selection of the rolling speed mode. Currently, the rolling is carried out at a constant speed of rotation of the rolls and the minimum permissible feed. The possible number of revolutions of the rolls is calculated from the condition of the permissible acceleration of braking of the feeder during its approach to the rolls during the idling period. The maximum permissible acceleration of braking, which depends on the force of adhesion of the sleeve to the mandrel, is determined from the condition of the absence of slipping of the sleeve from the mandrel during the rolling period [1 1]. In the initial rolling period (during seeding), the adhesion of the sleeve to the mandrel is minimal, and then increases as rolling progresses. Therefore, to increase the rolling speed during seeding, it is necessary to increase the adhesion of the sleeve to the mandrel. This can be done by preliminary preparation of the front or rear end of the sleeve on the mandrel;

8. Preliminary preparation of the front (rear) ends of the sleeves [12]. The use of a pre-sharpened sleeve end immediately eliminates the first stage of the seeding, which reduces its duration and ensures the sleeve is set beyond the line of the roll centers. Due to a significant increase in the feed (not exceeding the critical one), a significant reduction in the duration of the second stage can be achieved, which, with a length of the pointed end equal to half the pilger head, should ensure a reduction in the seeding duration by 50%. In the case of synchronization of the roll-feeder system with a length of the pointed end of the sleeve equal to half the length of the pilger head, the seeding duration could be significantly reduced. The length of the end section and its profile correspond to the length of the pilger head and the shape of the pilger roll striker. However, obtaining such a profile of the end section from the point of view of sharpening technology is irrational due to the deterioration of quality due to significant intercellular deformation and the acceleration of the end section of the sleeve before the pilgrim rolling. As a result of our research, the shape of the end section was recommended, in which the length of the sharpened end of the sleeve is approximately half the length of the pilger head.

Let us consider a refined classification of methods for preparing the front ends of sleeves on a pilgrim unit with a piercing press and an elongator mill (Fig. 4).

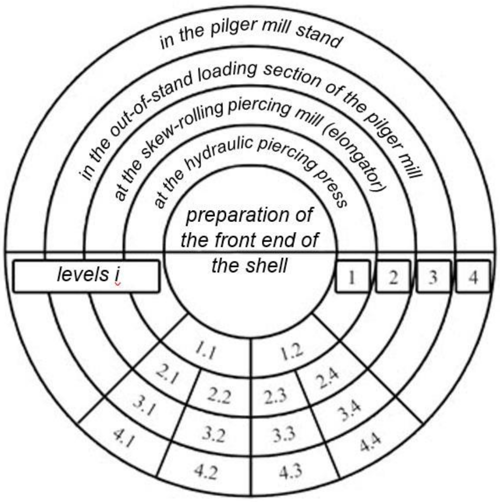

Fig. 4. Classification of methods for preparing the front ends of sleeves on a pilgrim unit with a piercing press and a cross-roller elongator mill

Preparation of the front ends of the sleeves before pilgrim rolling is possible at each of the four technological levels. The first level is the piercing press, the second level is the piercing cross-roller mill (elongator), the third level is the off-stand charging section of the pilgrim mill, and the fourth level is the pilgrim mill stand.

On the unit with a piercing hydraulic press, the following basic preparation methods are possible. At the first level: 1.1 - in the process of piercing the workpiece into the sleeve with a mandrel with subsequent rolling of the sleeves into pipes on the pilger mill, and the profiling of the front ends of the sleeve is carried out with support punches with a change of the profile sleeve; 1.2 - first, the profiling of the front end of the workpiece is carried out, and then the compression in diameter and wall thickness is carried out by moving the matrix along the workpiece to its rear end. At the second level, the following basic preparation methods of the front ends of the sleeves are possible during the rolling of the cups after the press on the oblique roll elongator mill : 2.1 - in the process of rolling on the output side of the elongator mill stand with idle rolls; 2.2 - the same with profiled matrices; 2.3 - changing the rolling angle of the working rolls of the elongator mill; 2.4 - change in the spacing of the working rolls under the load of the elongator.

At the third level, the following basic methods of preparing the front ends of the sleeves are possible: 3.1 - by pressing with the punches of a hydraulic press on the mandrel; 3.2 - on a planetary-type rolling machine or cross-screw flattening; 3.3 - by longitudinal flattening in stream rolls; 4.4 - pushing the sleeve onto the mandrel in the idle roll or matrix. At the fourth level, the following basic methods of preparing the front ends of the sleeves are possible: 4.1 - by preliminary pressing with pilgrim rolls with increased roll spacing; 4.2 -

by pressing with press matrices in front of the stand; 4.3 - by pressing the sleeve end behind the stand with press matrices under the condition of the rolled rolls being spaced; 4.4 - limiting the position of the front end of the sleeve in front of the rolls using profile sectors placed in the mill stand [13].

A feature of the preparation of the front end of the sleeve with idle rolls on a piercing mill (elongator) is the presence of deformation of the sleeve section between the drive and idle rolls, which is subjected to the forces of axial support and twisting. In this case, the increase in the diameter of the sleeve should not exceed 2%, so as not to complicate the process of pilgrim rolling. Studies of pilgrim rolling of pipes from sleeves with prepared front ends have established a decrease in metal consumption by 5-14 kg/t due to a decrease in the front end cut and the duration of the seeding process by 25-30% (depending on the pipe assortment). The experience of using the TPA 5-12" elongator mill with pilgrim mills for running in the front end of the sleeve with idle rolls allowed us to determine the advantages and disadvantages of this technology, which should be used to improve it. The second most realistic way to prepare the front ends of the sleeves is to crimp the front end of the sleeve on a mandrel with profiled half-matrixes on a hydraulic press.

Further development of the technology of preparing the front ends of the sleeve in the area of off-station loading is the work [5], which proposed two new solutions for preparing the sleeve in a four-jaw press with the sleeve canting at 45° between two compressions by longitudinal jabs (Fig. 5) and on a planetary-type rolling machine (Fig. 6). A feature of the new solutions is that the preparation of the front ends of the sleeves is carried out in both the first and second cases on equipment placed between two pilgrim stands, which reduces the equipment park. In this case, the preparation of the front ends of the sleeves is carried out on a temporary short mandrel, the diameter of which is equal to the diameter of the pilger mandrel.

The objectives of preparing the rear ends of the sleeves before pilgrim rolling are to facilitate the conditions for loading the mandrel into the sleeve, improve the conditions of the seeding and steady-state processes by reducing the gap between the sleeve and the mandrel, increase the adhesion of the sleeve to the mandrel before rolling to reduce the cutting of the seeded ends of the pipes and reduce the seeding time, increase the rolling speed on the pilger mill without the sleeve slipping off the mandrel during the period of sleeve braking when it rolls into the rolls. Reducing the gap between the sleeve and the mandrel was proposed by increasing the inner diameter of the sleeve at its rear end on the cross-rolling piercing mill by moving the short conical mandrel of the mill against the direction of rolling from the moment the rear end of the workpiece approaches the rolls by a distance ΔLx so that the thinning of the sleeve wall at the rear end was within 2-6 mm [14].

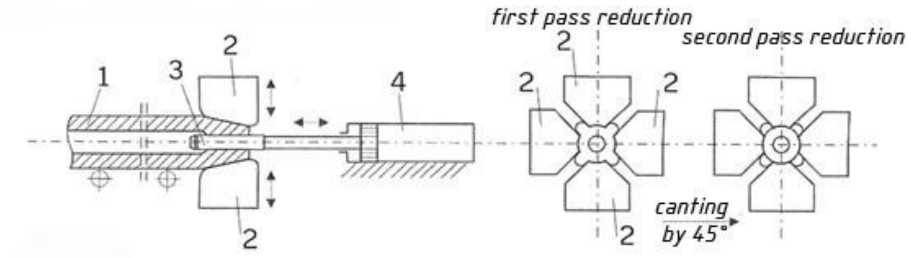

Fig. 5. Scheme of preparation of the front end of the sleeve on a four-jaw hydraulic press: 1- sleeve, 2- press jaws, 3- mandrel, 4- mandrel hydraulic drive

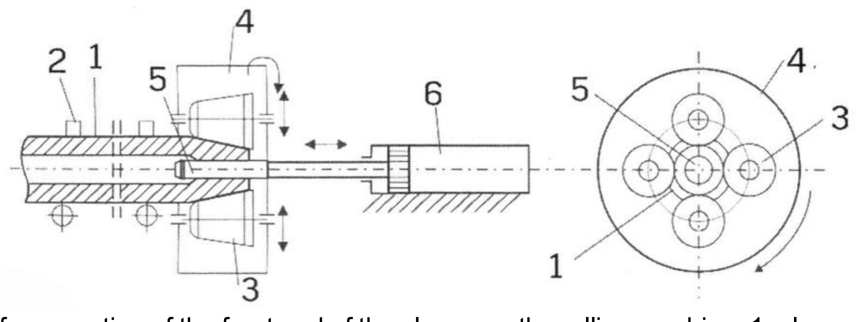

Fig. 6. Scheme of preparation of the front end of the sleeve on the rolling machine: 1- sleeve, 2- clamp, 3- idle rollers, 4- faceplate, 5- mandrel, 6—mandrel hydraulic drive

To increase the adhesion of the sleeve to the mandrel, it is proposed to prepare the rear end of the sleeve before pilgrim rolling by pressing it on a two-hammer horizontal hydraulic press with the deforming faces of the hammers arranged at an angle of 90° (Fig. 7).

The condition for holding the sleeve on the mandrel during its insertion into the rolls is

$P_{тр} \geq P_{ін}$,

where $P_{тр}$ is the friction force at the contact of the sleeve with the mandrel; $P_{ін}$– inertial force applied to the sleeve.

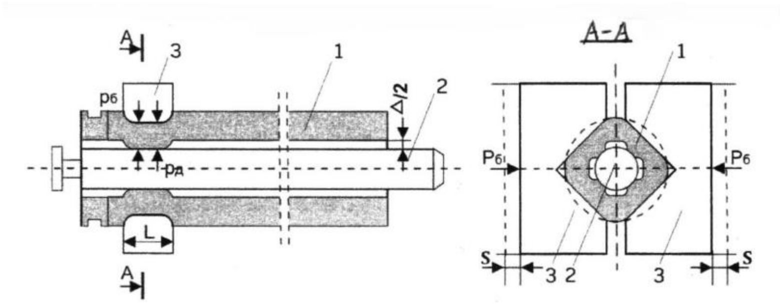

Fig. 7. Scheme of crimping the rear end of the sleeve on a two-jaw horizontal press: 1-sleeve, 2 – mandrel, 3 – press jabs

Analysis of known processes of preparation of front ends of sleeves shows that a common drawback for them is the acceleration of the front prepared end of the sleeve. This is due to the cooling of the sleeve, starting from the piercing mill (elongator) during its movement to the pilger mills. It should be noted that the sleeve after the elongator loses almost 100°C, to this it is necessary to add movement on the roller table and movement in the area of out-of-station loading. All this leads to a significant acceleration of the thinned end of the sleeve, which worsens the conditions of the seeding, primarily with an increase in the load on the rolls, deterioration of the quality of their working surface and increased risk of accidents.

To reduce these disadvantages: the elongator roller table must be made heat-shielding, a heated thermostat must be located in the off-stand charging area to stabilize the sleeve temperature not lower than the critical one, and a metal temperature monitoring system must function on the rolling mill both on the mills and between the mills.

Combined use of methods for improving the seeding regime. The greatest deterioration in the technical and economic indicators of pilgrim rolling occurs during the production of thin-walled D/S=12.5-40.0 and especially thin-walled D/S>40 pipes due to the features mentioned above. The seeding conditions during the production of thick-walled D/S=6.0-12.5 and especially thick-walled pipes D/S<6 are much better, however, even in this case there is a solution to improve the production of these pipes.

For an axisymmetric position of the sleeve on the mandrel before rolling on a pilgrim mill, a combined preparation of the front and rear ends of the sleeves is proposed, which will ensure uniformity of the gap between the sleeve and the mandrel and thereby increase the accuracy of the pipes in terms of wall thickness by reducing the transverse wall difference. This measure is effective in obtaining pipes of the entire assortment. Several options are possible for this. According to the first option, the front and rear ends of the sleeve are crimped on the mandrel in the area of out-of-the-mill charging. According to the second option, a mandrel with a conical belt near the shank is used, which will allow the rear end of the mandrel to be distributed and the gap to be eliminated.

Possible combinations of methods 1-8 are given in Table 1, taking into account the ratio D/S, steel grade, use of old or modernized feeders. For a modernized pilgrim unit, the task of choosing a set of methods to improve the seeding regime is solved from the point of view of economic feasibility, taking into account the above factors and production volumes.

Table 1. Combined use of basic methods for improving the seeding regime

No. s/n	Method	Method number							
		1	2	3	4	5	6	7	8
1	Reducing the extraction coefficient on the pilger mill	AND	AND			AND	AND	AND	
2	Increasing the adhesion of the sleeve to the mandrel before rolling	AND	AND			AND	AND		
3	Using special rings		B	B		B			
4	Butt-rolling of sleeves	B			B			B	
5	Forced 90° tilting of sleeves during seeding	AND				AND			AND
6	Choosing a rational feeding regime during seeding	AND	AND				AND		
7	Selecting the rolling speed mode		AND		B			AND	
8	Preliminary preparation of the front (rear) ends of the sleeves					AND	AND	AND	AND

A - thin-walled pipes D/S= 12.5 – 40.0 (especially thin-walled pipes D/S>40)
B - thick-walled pipes D/S= 6.0 - 12.5 (especially thick-walled pipes D/S> 6)

Conclusions

1. The presence of an unstable seeding mode of hot pilgrim rolling of pipes reduces the technical and economic indicators of pilgrim rolling, especially of thin-walled pipes, which leads to a decrease in the productivity of the pilgrim mill by 1.2 - 1.5% and an increase in the metal consumption factor by 2-3%.

2. An analysis of known methods for improving the conditions of the seeding regime was carried out and the prospects for their use for thin-walled and thick-walled pipes were determined.

3. The maximum positive impact on the conditions

of the seeding mode is made by the preparation of the ends of the sleeves before the pilgrim rolling. Two new technologies for preparing the front ends of the sleeves on a four-punch press and on a planetary-type rolling machine are proposed, as well as two new technologies for preparing the rear ends of the sleeves, the first of which is carried out on a cross-roller piercing mill due to the movement of the mandrel, which thins the wall of the rear end of the sleeve and helps reduce the gap between the sleeve and the mandrel. The second technology consists in pressing the rear end of the sleeve on the mandrel in order to increase the adhesion between them at the beginning of rolling, which improves the conditions of the seeding mode and increases the rolling speed.

4. The most effective is the combined use of the considered methods of improving the seeding regime, taking into account the specific composition of the equipment of the pilgrim unit, the assortment of pipes being rolled, the tonnage of a specific order. The D/S parameter of the pipes being rolled is of particular importance, since the choice of certain methods of improving the seeding process depends on it.

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Удосконалення методик та програмного забезпечення технологічного проектування ділянок холодної роликової прокатки

Soloviova I.A., Nykolaienko Yu.M., Balakin V.F.

Improvement of methods and software for technological design of cold roller rolling sections

Анотація. *Мета роботи – розробка математичних моделей параметрів деформації для прокатці на станах ХПТР з впровадженням їх до програмного забезпечення технологічного проектування ділянок ХПТР. Даними для отримання моделей є практичні та експериментальні маршрути виробництва нержавіючих труб різного сортаменту на станах ХПТР. Дані структуровані та використано кореляційно-регресійний аналіз для моделювання. На основі отриманих моделей параметрів деформації розроблено програмне забезпечення, що вирішує питання проектування маршрутів виробництва холоднодеформованих труб на станах ХПТР. Результати роботи дають можливість скорочувати час проектування маршрутів та технології виробництва, отримувати нові варіанти маршрутів для вибору та оптимізації виробництва з метою скорочення проходів маршруту, витратного коефіцієнту металу та аналізу навантаження на обладнання.*
Ключові слова: *абсолютне обтиснення, деформація, математична модель, заготовка, труба, статистичний аналіз.*

Abstract. *The purpose of the work is to develop mathematical models of deformation parameters for rolling on CPTR mills with their implementation in the software for technological design of CPTR sections. The data for obtaining models are practical and experimental routes for the production of stainless-steel pipes of various assortments on HPTR mills. The data was structured and correlation-regression analysis was used for modeling. Based on the obtained deformation parameter models, software was developed that solves the issue of designing routes for the production of cold-formed pipes on CPTR mills. The results of the work make it possible to reduce the time for designing routes and production technologies, obtain new route options for selection and optimization of production in order to reduce route passes, metal consumption coefficient, and analyze the load on equipment.*
Keywords: *absolute compression, deformation, mathematical model, workpiece, pipe, statistical analysis.*

Introduction. Despite the rapid development of highly intelligent technologies, it is impossible to imagine modern human life without metallurgy. Since this is the industry whose products, we use every day. Engineering activities are associated with the use of modern information technologies, computer programs, the ability to perform modeling, forecasting, programming to perform technological calculations at a professional level, implement them in the existing technological process and develop new production technologies.

Problem statement. The production of cold-deformed pipes of the same assortment leads to the use of different technological schemes for their manufacture, from blanks of different sizes for a different number of deformation cycles. When designing variants of routes for the production of cold-deformed pipes, it is necessary: to use in each pass of the route all possible variants of equipment for cold rolling of metal, to limit oneself to unified sizes of diameters and wall thickness of blanks, to limit the sizes of the initial blank to the assortment of blanks and to use deformation modes that ensure maximum use of the plastic properties of the metal, these problems were raised when designing routes for the production of cold-deformed pipes of a separate assortment and for some groups of steels [1-5].

The purpose of the work is to develop mathematical models of deformation parameters for rolling a wide range of pipes for different groups of steels that have formed with the same deformation parameters on the CPTR mills, with their implementation in the software for technological design of CPTR sections, which is useful for designers, production specialists, researchers and students when performing course and diploma theses.

Research methods. The operating modes of the CPTR mills introduced at Ukrainian pipe plants, known methods of route calculations [1-5] were analyzed, data were generalized and regression models of deformation parameters were derived for new groups of steels and a wide range of products were derived. Algorithms were constructed, according to which software for calculating pipe production routes on CPTR mills was developed. In order to improve the methods of calculating deformation parameters, regression-correlation analysis of generalized experimental and practical data was performed. Various approximation models were carefully analyzed and the most accurate ones were selected, according to which the corresponding software for calculating routes was developed.

Results of the study Analysis of routes and technological maps of stainless-steel pipe production at Ukrainian pipe plants led to the unification of the assortment of stainless-steel cold-formed pipes into 8 following groups (table 1) [1-6]. The purpose of unifying the assortment is to identify the same deformation parameters in the production of cold-formed pipes on CPTR mills. The maximum permissible compressions in diameter ($\Delta D_{\max}$) for pipes of each group of steels of the considered assortment, changes in wall thickness during rolling of pipes of different assortment on CPTR mills were determined based on practical and experimental data.

Table 1 - Assortment of cold-formed pipes by steel groups

Group	Type of pipes
1	General purpose (austenitic stainless steel)
2	High quality (austenitic stainless steel)
3	General purpose (stainless ferritic)
4	With particularly high quality and precision requirements (stainless and carbon)
5	General purpose (10, 20, 15X, 20X, 20K, 10G2)
6	Improved quality (20A, 35, 15XM, 15X5M, 30XMA, 50XMA, 38XA, 38XMUA, 40X, 12X1MF, 12XN3A)
7	Hardly deformable (45, 50, 30KhGSA, EI-712)
8	Special thin-walled austenitic stainless steels

An algorithm for determining workpiece dimensions when designing production routes has been developed, which is represented by the following calculation stages:

The maximum diameter of the workpiece before passing through the CPTR mill is defined as:

$$D_0 \le D_{got} + \Delta D_{\max}, \qquad (1)$$

where $D_{got}$is the diameter of the finished pipe, mm;

D_0– workpiece diameter, mm;

$\Delta D_{\max}$- maximum crimping diameter, mm.

The steel groups hereinafter correspond to the groups indicated in Table 1.

Data received$\Delta D_{\max}$ are presented as graphs of dependence on the size of the finished product and approximated by regression equations. The results of the approximation are presented in Figures 1, 2.

The graphs below show pointwise practical and experimental data that are approximated by regression equations. Figures 1-5 – Definition of regression models$\Delta D_{\max}$ for different steel groups and assortment. Figures 6-7 – definition of regression models for calculating the wall thickness of the workpiece.

Comparison of statistical data and calculations using regression models (Fig. 1, 2) allows us to select models (1, 2) that are accepted for automated route calculation for 1-3 product groups:

$$\Delta D = 1{,}6481\ln(D) - 1{,}5542, \qquad (1)$$

for 4-7 product groups:

$$\Delta D = 0{,}8241\ln(D) + 0{,}2229. \qquad (2)$$

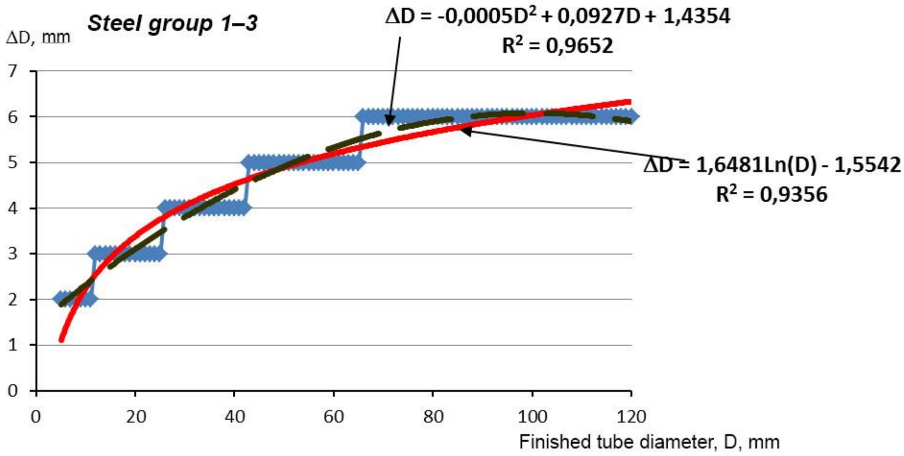

Fig. 1. Maximum pipe compression by diameter$\Delta D_{\max}$ on CPTR mills for steel groups 1-3

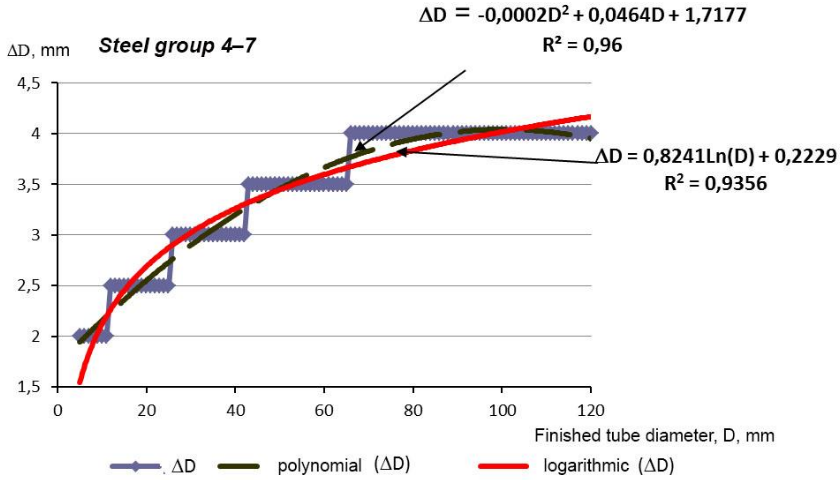

Fig. 2. Maximum pipe diameter crimping $\Delta D_{\max}$on CPTR mills for steel groups 4-7

For ultra-thin-walled stainless steel pipes (group 8), the dependence $\Delta D$was studied on D, t, $t/D$for the states ХПТР 6-15, ХПТР15-30, ХПТР 30-60 (Fig. 3-5). The points on the graphs correspond to practical data, the curved lines are approximations of the data by equations.

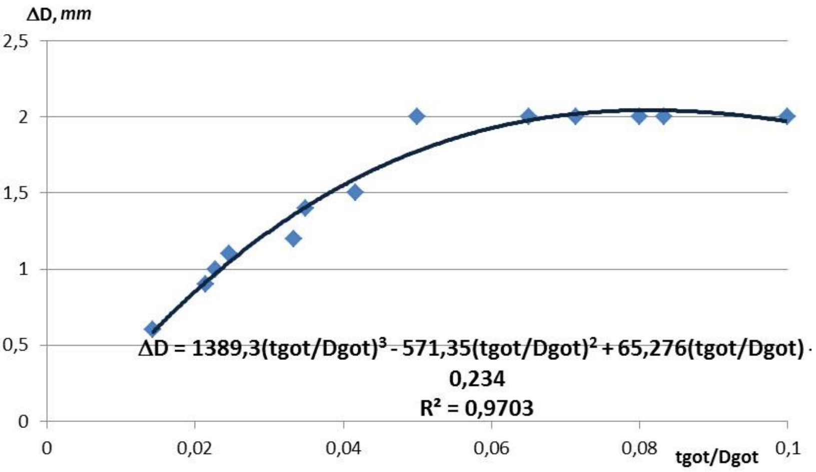

Fig. 3. Maximum pipe diameter crimping on CPTR 6-15 mills for steel groups 8

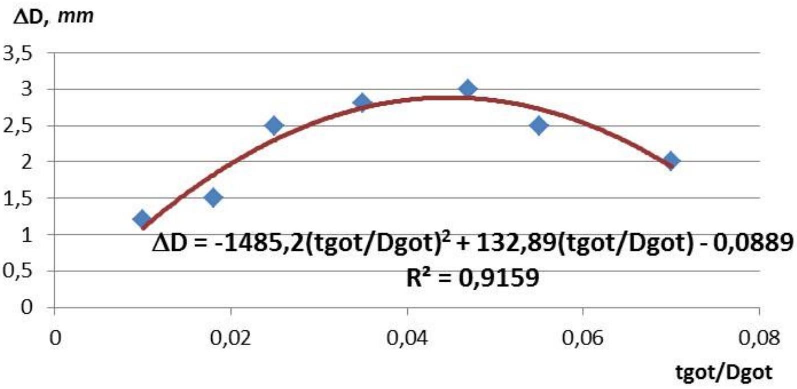

Figure 4 - Maximum pipe diameter crimping on CPTR 15-30 mills for steel groups 8

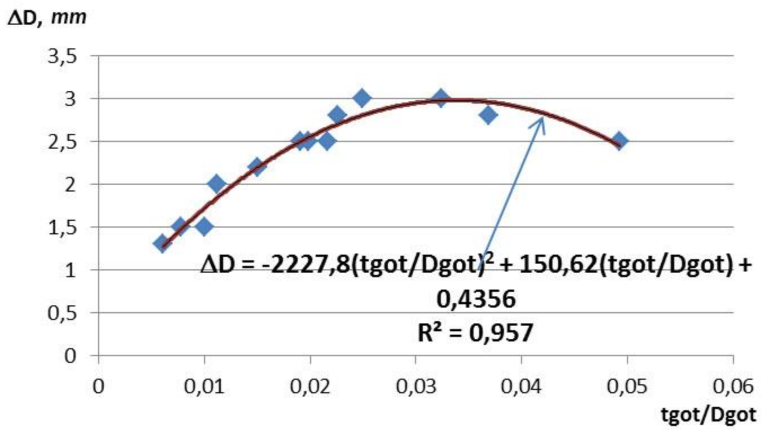

Fig. 5. Maximum pipe diameter crimping on CPTR 30-60 mills for steel group 8

To calculate the thickness of the workpiece wall, we analyzed practical and experimental data for each CPTR state (for groups 1-3, these are CPTR states 8-15, 15-30, 30-60, 60-120, Fig. 6, for group 8, CPTR states 6-15, 15-30, 30-60, Fig. 7) and obtained models for each CPTR state.

In Figures 6-7 the following notations are used:
t_{got} – wall thickness of the finished (reducing) pipe;
t_z– the thickness of the workpiece wall.

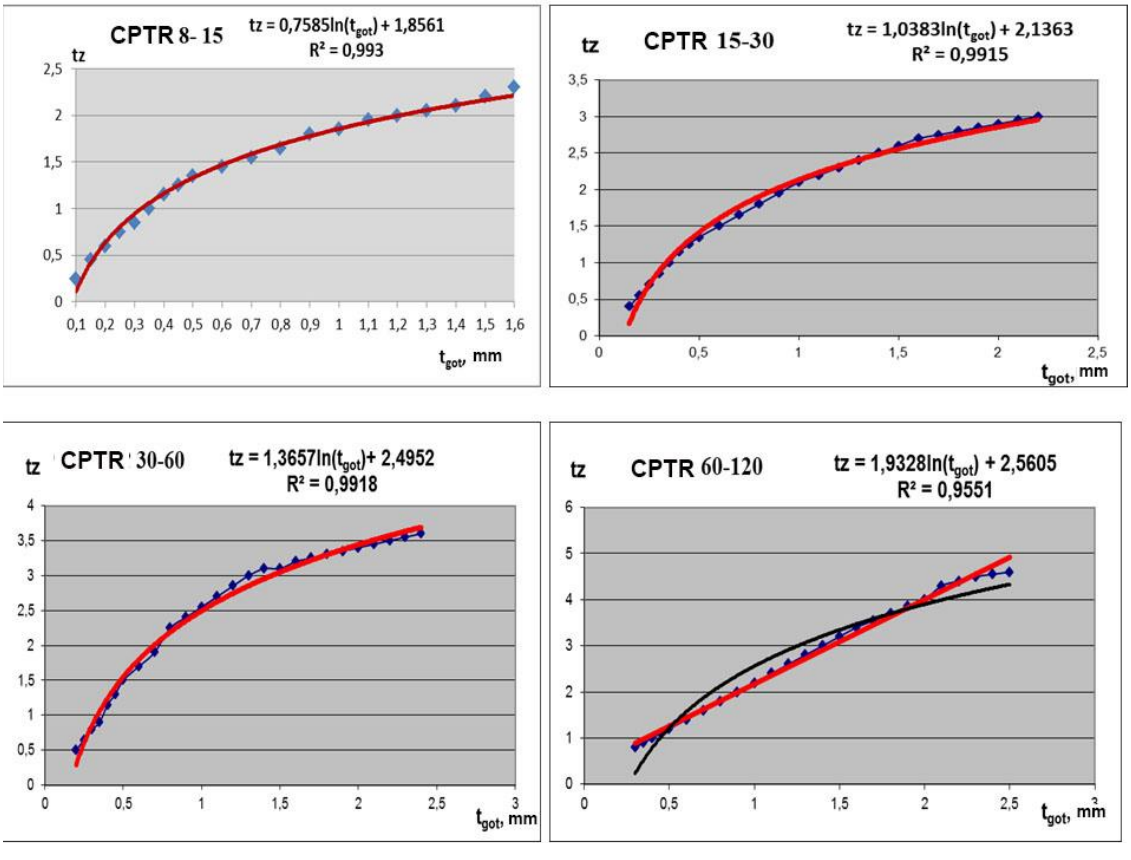

Fig. 6. Approximation by regression models of the values of the billet wall thickness according to data for pipes made of stainless-steel grades (Groups 1-3)

For carbon and alloy steels (group 4-7):
status of the CPTR 8-15:
$t_z = 0{,}4858 \cdot \ln(t_{\text{got}}) + 1{,}6734;$
status of the CPTR 15-30:
$t_z = 0{,}7047 \cdot \ln(t_{\text{got}}) + 1{,}9517.$

The type of dependence of the wall thickness of the billet on the wall thickness of the finished pipe is logarithmic $t_z = a \cdot \ln(t_{\text{got}}) + b$, where the coefficients $a,$ ⇄ ⇄ $b$are determined by the type of mill. For the use of models in the program for calculating routes, equations

(6) were unified $t_z(t_{\text{got}}, stan())$for steel groups 1-3, where $stan$ - types of CPTR: 8, 15, 30, 60:

$$a = 0{,}0217 \cdot s\,tan + 0{,}661 \qquad (4)$$

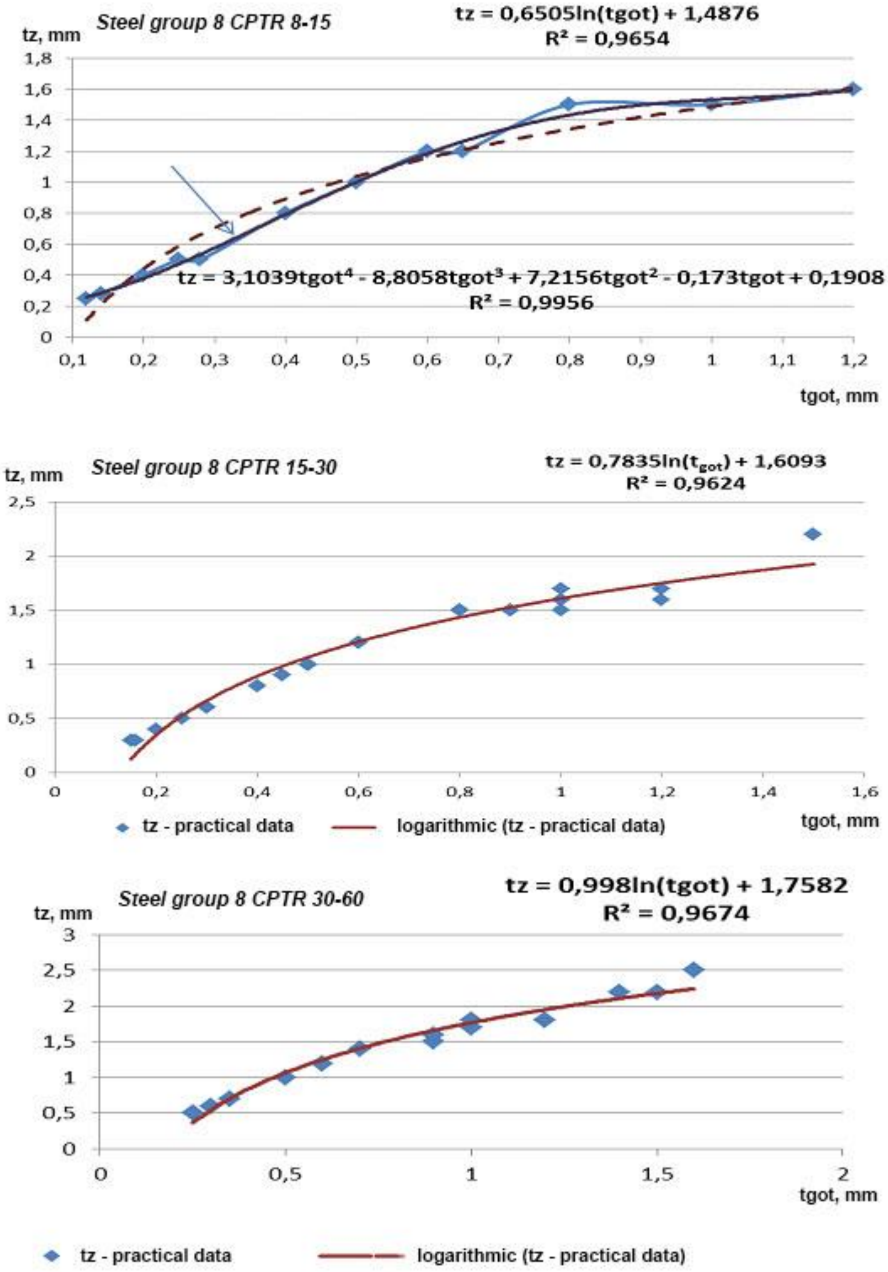

Fig. 7. Approximation by regression models of the values of the billet wall thickness according to data for ultra-thin-walled pipes made of stainless-steel group (Group 8) for grades CPTR 6-15, CPTR 15-30, CPTR 30-60

$$b = 0{,}3657 \cdot ln(stan()) \qquad (5)$$

Unified equation for steel groups 1-3 and corresponding CPTR states:

$$t_z = (0{,}0217 \cdot s\,tan + 0{,}661) \cdot ln(t_{got}) + (0{,}3657 \cdot ln(stan())\,()) \quad (6)$$

A similar dependence of the workpiece wall thickness was obtained for ultra-thin-walled stainless steel pipes (steel group 8) – Figure 7.

Unified equation for determining the wall thickness of the workpiece for group 8 (7):

$$t_z = (0{,}0145 \cdot s\,tan + 0{,}5647) \cdot ln(t_{got}) + (0{,}0111 \cdot ln(stan())\,()), \quad (7)$$

where the parameter $stan$takes the value according to the type of state of the steel CPTR - 6, 15, 30.

Taking into account the research, a program for calculating routes on the CPTR mills has been developed. Examples of calculations are given in Figures 8-10.

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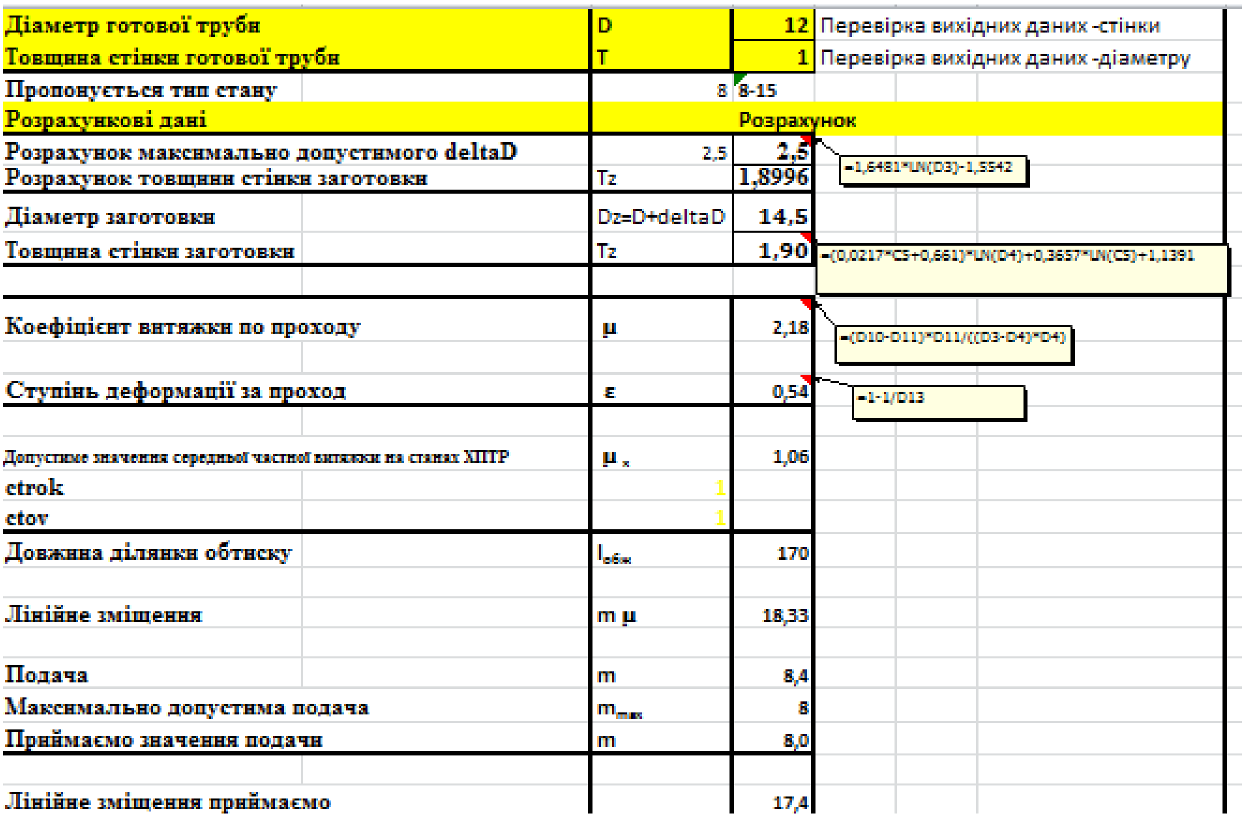
Table 2. Summary table of models for calculating the wall thickness of the workpiece

State of the CPTR (steel groups 1-3)	Regression model t_z - wall thickness of the workpiece, t_{got}–wall thickness of the finished pipe	State of the CPTR (groups of steels 1-I3)	Regression model t_z - wall thickness of the workpiece, t_{got}–wall thickness of the finished pipe
CPTR 8-15	$t_z = 0{,}7585 \cdot \ln(t_{\text{got}}) + 1{,}8561$ R^2=0.993	CPTR 30-60	$t_z = 1{,}3657 \cdot \ln(t_{\text{got}}) + 2{,}4952$ R^2= 0.9918
CPTR 15-30	$t_z = 1{,}0383 \cdot \ln(t_{\text{got}}) + 2{,}1363$ R^2= 0.9915	CPTR 60-120	$t_z = 1{,}9328 \cdot \ln(t_{\text{got}}) + 2{,}5607$ R^2= 0.9551
State of the CPTR (groups of steels 4-7)	Regression model t_z - wall thickness of the workpiece, t_{got}–wall thickness of the finished pipe	State of the CPTR (steel groups 4-7)	Regression model t_z - wall thickness of the workpiece, t_{got}–wall thickness of the finished pipe
CPTR 8-15	$t_z = 0{,}4858 \cdot \ln(t_{\text{got}}) + 1{,}6734$	CPTR 15-30:	$t_z = 0{,}7047 \cdot \ln(t_{\text{got}}) + 1{,}9517$
CPTR 6-15 (gr. st. 8)	$t_z = 0{,}6505 \cdot \ln(t_{\text{got}}) + 1{,}4876$ R^2= 0.9654		
CPTR 15-30 (gr. st. 8)	$t_z = 0{,}7835 \cdot \ln(t_{\text{got}}) + 1{,}6093$ R^2= 0.9624		
CPTR 30-60 (gr. art. 8)	$t_z = 0{,}998 \cdot \ln(t_{\text{got}}) + 1{,}7582$ R^2= 0.9674		



Діаметр готової труби	D	12	Перевірка вихідних даних -стінки
Товщина стінки готової труби	T	1	Перевірка вихідних даних -діаметру
Пропонується тип стану	8	8-15	
Розрахункові дані		Розрахунок	
Розрахунок максимально допустимого deltaD	2,5	2,5	=1,6481*LN(D3)-1,5542
Розрахунок товщини стінки заготовки	Tz	1,8996	
Діаметр заготовки	Dz=D+deltaD	14,5	
Товщина стінки заготовки	Tz	1,90	=(0,0217*C5+0,661)*LN(D4)+0,3657*LN(C5)+1,1391
Коефіцієнт витяжки по проходу	μ	2,18	=(D10-D11)*D11/((D3-D4)*D4)
Ступінь деформації за проход	ε	0,54	=1-1/D13
Допустиме значення середньої частної витяжки на станах ХПТР	μ x	1,06	
ctrok	1		
ctov	1		
Довжина ділянки обтиску	$l_{обж}$	170	
Лінійне зміщення	m μ	18,33	
Подача	m	8,4	
Максимально допустима подача	m_{max}	8	
Приймаємо значення подачи	m	8,0	
Лінійне зміщення приймаємо		17,4	

Figure 8 – Calculation of the route 14.5x1.9—12x1mm CPTR8-15, group 1

Розрахунок маршруту прокатки Тип проходу		Група сталей	1
Вихідні дані	Позначення		
Діаметр готової труби	D	17	Перевірка вихідних даних -стінки
Товщина стінки готової труби	T	0,5	Перевірка вихідних даних -діаметру
Пропонується тип стану	15	15-30	
Розрахункові дані		Розрахунок	
Розрахунок максимально допустимого deltaD	5,1	3	
Розрахунок товщини стінки заготовки	Tz	1,4456	
Діаметр заготовки	Dz=D+deltaD	20	
Товщина стінки заготовки	Tz	1,45	
Коефіцієнт витяжки по проходу	μ	3,25	=(D10-D11)*D11/((D3-D4)*D4)
Ступінь деформації за прохід	ε	0,69	=1-1/D13
Допустиме значення середньої частної витяжки на станах ХПТР	μ x	1,05	
ctrok	1		
ctov	2		
Довжина ділянки обтиску	lобж	170	
Лінійне зміщення	m μ	11,98	
Подача	m	3,7	
Максимально допустима подача	mmax	9,2	
Приймаємо значення подачі	m	3,7	
Лінійне зміщення приймаємо		12,0	

Fig. 9. Calculation of the route passage 20x1.45—17x0.5 CPTR 15-30, group 1

Розрахунок маршруту прокатки Тип проходу		Група сталей	1
Вихідні дані	Позначення		
Діаметр готової труби	D	20	Перевірка вихідних даних -стінки
Товщина стінки готової труби	T	1,45	Перевірка вихідних даних -діаметру
Пропонується тип стану	15	15-30	
Розрахункові дані		Розрахунок	
Розрахунок максимально допустимого deltaD	5,4	3,5	
Розрахунок товщини стінки заготовки	Tz	2,4960	
Діаметр заготовки	Dz=D+deltaD	23,5	
Товщина стінки заготовки	Tz	2,50	
Коефіцієнт витяжки по проходу	μ	1,95	=(D10-D11)*D11/((D3-D4)*D4)
Ступінь деформації за прохід	ε	0,49	=1-1/D13
Допустиме значення середньої частної витяжки на станах ХПТР	μ x	1,05	
ctrok	1		
ctov	2		
Довжина ділянки обтиску	lобж	170	
Лінійне зміщення	m μ	17,03	
Подача	m	8,7	
Максимально допустима подача	mmax	9,2	
Приймаємо значення подачі	m	8,7	
Лінійне зміщення приймаємо		17,0	

Fig. 10. Calculation of the route passage 23.5x2.5 -20x1.45 CPTR 15-30 group 1

Comparing the calculated routes with the existing ones makes it possible to propose routes for a new assortment, with other equipment options and with a reduction in the number of passes (Table 3).

Table 3. Calculated routes (st.12X18N10T, gr. I)

No.	Manufacturing route	Types of deformation
1	23x2.5 20x1.45 17x0.5 goth	 CPTR 15-30 CPTR 15-30
2	43x3.65 39x2.6 35x1.2 Got	 CPTR 30-60 CPTR 30-60
3	15x2.3 12x1.6 10x0.75 8x0.25 Got	 CPTR 8-15 CPTR 8-15 CPTR 8-15
4	23x2.5 20x1.5 Got	 CPTR 15-30
5	10.5x1.3 8x0.5 Got	CPTR 8-15

Conclusions

The developed mathematical models and calculation program solve the issue of designing rolling routes on CPTR mills for different groups of steels, which reduces the time for designing routes, allows for the optimal selection of routes with fewer passes compared to the current ones, which, in turn, leads to savings in production time and metal consumption .

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Гришин О.М., Іващенко В.П., Надточій А.А., Безшкуренко О.Г., Чімишенко Т.Ю.

Вплив енергетичної та хіміко-каталітичної інтенсифікації відновлення заліза на окислюваність металізованого продукту

Grishin O.G., Ivashchenko V.P., Nadtochii A.A., Bezshkurenko O.G., Chimyshenko T.Yu.

The influence of energetic and chemical-catalytic intensification of iron reduction on the oxidizability of the metallized product

Анотація. *Мета. Метою роботи є аналіз впливу електромагнітного поля та каталітичних добавок на параметри процесу окислення відновленого губчастого заліза. Методика. Експерименти проводили у змінному магнітному полі з використанням термогравіметричної методики. Процес окислення досліджували із визначенням температури початку окислення та ступеня окислення. Результати. Результати лабораторних експериментів свідчать про вплив електромагнітного поля на процес окислення продуктів твердофазного відновлення заліза. Введення каталітичних добавок у відновлювану шихту позитивно впливає на окислюваність продукту. Низькочастотне поле підвищувало температуру початку окислення та знижувало ступінь окислення. Наукова новизна. Експериментально підтверджено вплив електромагнітного поля (ЕМП) на температуру початку окислення, ступінь та швидкість окислення металізованого продукту. Запропоновано механізм пасивуючої дії ЕМП та каталітичних добавок на відновлене залізо. Практична значущість. Отримані результати досліджень дозволяють знизити втрати при окисленні металізованого залізного порошку.*
Ключові слова: *твердофазне відновлення, пасивація, ступінь окислення, каталітичні добавки, змінне електромагнітне поле, механізм впливу ЕМП*

Abstract. *Purpose. The purpose of the work is to analyze the influence of the electromagnetic field and catalytic additives on the parameters of the oxidation process of reduced sponge iron. Methodology. The experiments were carried out in an alternating magnetic field using the thermogravimetric method. The oxidation process was studied with the determination of the temperature of the onset of oxidation and the degree of oxidation. Results. The results of laboratory experiments indicate the influence of the electromagnetic field on the oxidation process of solid-phase iron reduction products. The introduction of catalytic additives into the reducing charge has a positive effect on the oxidation of the product. The low-frequency field increased the temperature of the onset of oxidation and reduced the degree of oxidation. Scientific novelty. The influence of the electromagnetic field (EMF) on the temperature of the onset of oxidation, the degree and rate of oxidation of the metallized product was experimentally confirmed. The mechanism of the passivating effect of EMF and catalytic additives on reduced iron was proposed. Practical significance. The obtained research results allow to reduce losses during oxidation of metallized iron powder.*
Keywords: *solid-phase reduction, passivation, oxidation state, catalytic additives, variable electromagnetic field, mechanism of EMF influence*

Вступ

Технологія твердофазного відновлення заліза має ряд істотних переваг: відносно низькі температури, висока ступінь вилучення металу з рудного матеріалу та ін. Разом з тим продуктивність даної технології безпосередньо залежить від інтенсивності всіх сполучених ланок процесу хіміко-каталітичним чи енергетичним впливом. Разом з тим, практичне значення має отримання металізованого продукту з високими якісними показниками, і в першу чергу, його захист від окислення.

Результати дослідження та їх обговорення

Продукти низькотемпературного відновлення (металізації) залізорудних матеріалів, як правило, мають розвинену пористість і поверхню. Остання, з умов відновлення зазвичай характеризується значною невпорядкованістю кристалічної структури. Усе це створює сприятливі умови для вторинного окислення (і навіть самозаймання) металевого продукту киснем повітря [1-17]. Ступінь окислення ($\omega_{ок.}$) при зберіганні, транспортуванні, плавці, при подрібненні губки на порошок та ін. може бути дуже суттєвою. Вона залежить, серед інших причин [1, 11-17], від присутності у шихті активуючих добавок.

Тому продукти відновлення залізорудних матеріалів піддавалися нами перевірці на окислюваність киснем повітря [18]. Визначали температуру, за якої починається інтенсивний розвиток процесу ($T_{ок.}$). На установці з автоматичною безперервним зважуванням зразка вивчали кінетику окислення в різних температурних умовах. Витрата повітря в основній серії дослідів становила 0,3-0,4 л/хв. Закономірності, встановлені у дослідженнях, узгоджуються з літературними даними [1, 13-15].

Твердофазне відновлення заліза за невисоких температур призводить до отримання металізованого продукту, для якого характерна висока окислюваність на повітрі і навіть пірофорність (самозаймання) [19]. Це призводить до втрат заліза при видачі продукту на повітря, переплаву губки та ін. Ці втрати, що досягають кількох десятків відсотків, знижують техніко-економічні показники процесу. Незважаючи на те, що висока окислюваність губчастого заліза та порошків є однією з головних причин, що обмежують широке впровадження у промислове виробництво твердофазного відновлення, причини та фактори, що впливають на неї, та можливі заходи мінімізації вивчені недостатньо. Було досліджено окислюваність заліза, отриманого з Fe_2O_3 і Fe_3O_4, магнетитового концентрату і багатої залізної руди, при різних температурах і в звичайних умовах і з використанням енергетичних та хіміко-каталітичних впливів. Досліджено окислюваність заліза, отриманого при відновленні рудних матеріалів вуглецем, у потоці повітря за різних температур.

Щоб уникнути відкладення сажі, шихта відновлювалася при 873-973 К у потоці чистого водню. Встановлено, що метал, отриманий з магнетитового концентрату при 773 К, починав окислюватися в струмі повітря вже при 313 К. Процес протікав з високою швидкістю, але при ступені окислення ($\omega_{ок.}$) ~45 % сповільнюється і незабаром повністю зупиняється (рис. 1). Залізо, відновлене при 873 К, починає взаємодіяти з киснем повітря при 473 К та окислення протікає глибоко: $\omega_{ОК.}$ досягає майже 60 % (рис.2).

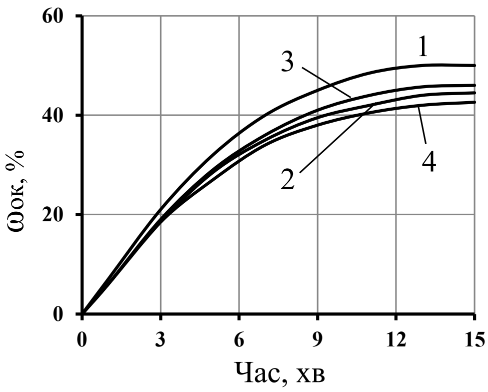


Рис. 1. Вплив ЕМП на окислюваність заліза при 313 К; залізо отримано з магнетитового концентрату (МК) при 773 К:

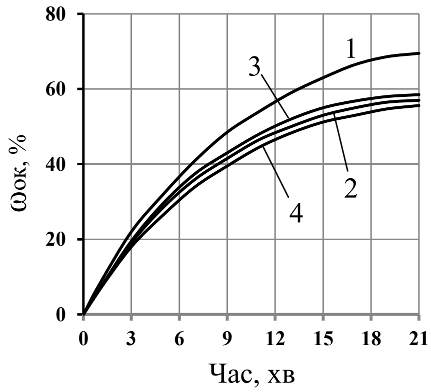


Рис. 2. Вплив ЕМП на окислюваність заліза при 483 К; залізо отримано з магнетитового концентрату (МК) при 873 К:

1 – поза полем; 2 – відновлення в полі; 3 – окислення у полі; 4 – відновлення та окислення в полі

Випробування каталізаторів – солей лужних металів – показало прискорення процесу відновлення та одночасно зростання окислюваності металізованої губки (рис. 3, 4). Продукт, отриманий при 773 і 873 К, у присутності хлориду калію взаємодіяв з киснем повітря дуже енергійно, кінцевий ступінь окислення $\omega_{ОК.}$ досягав ~80 %. Зниження витрати повітря сильно знижувало швидкість окислення, особливо в початковому періоді, проте граничний ступінь окислення не змінювався (рис.5).

Окислюваність заліза, отриманого з гематиту та магнетиту відновленням СО при підвищених температурах: 1073-1173 К, також зростала у присутності KCl. Це виявлялося в деякому зниженні температури початку окислення та у суттєвому зростанні швидкості процесу та величини граничної $\omega_{ОК.}$ (рис. 6, 7).

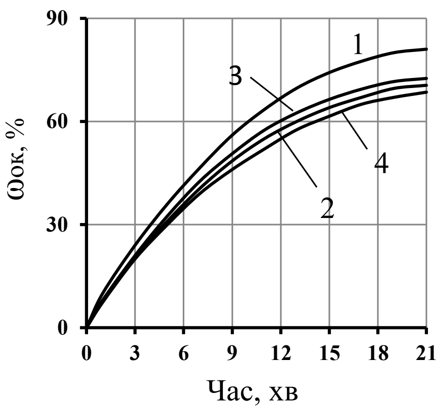


Рис. 3. Вплив ЕМП на окислюваність заліза при 313 К; залізо отримано з МК при 773 К та 1 % KCl:

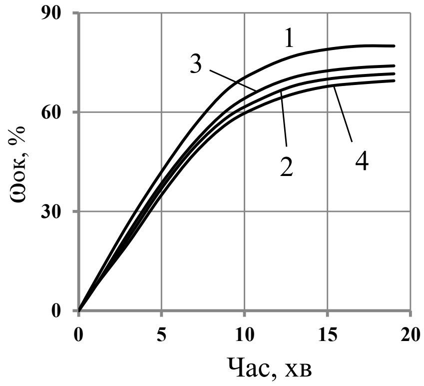


Рис. 4. Вплив ЕМП на окислюваність заліза при 483 К; залізо отримано з МК при 873 К та 1 % KCl:

1 – без поля; 2 – відновлення в полі; 3 – окислення у полі; 4 – відновлення та окислення в полі

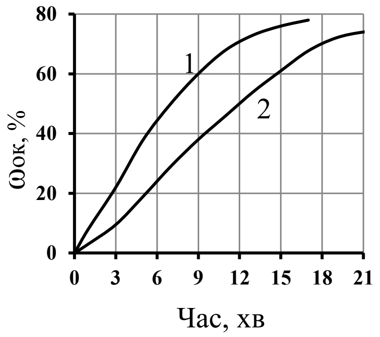


Рис. 5. Вплив швидкості повітряного потоку на окислюваність заліза при 312 К; залізо отримано з МК при 773 К, у присутності 1 % KCl:
1 – *W*=0,4 л/хв; 2 – *W*=0,2 л/хв

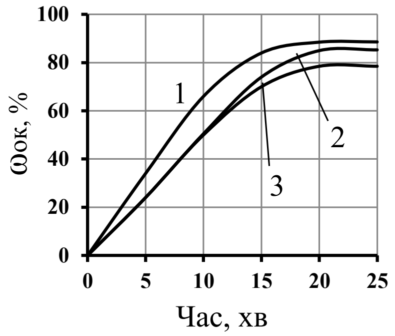


*Рис. 6 Хіміко-каталітичний вплив на окислюваність заліза (1073 К) при температурах початку процесу:*1 – 1 % KCl, $T_{ок.}$ = 433 К; 2 – без добавки, $T_{ок.}$ = 473 К; 3 – 1 % LiCl, $T_{ОК.}$ = 623 К

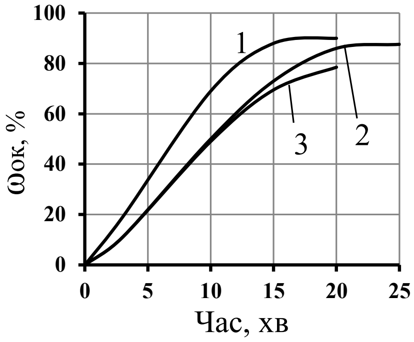


Рис. 7. Хіміко-каталітичний вплив на окислюваність заліза (1073 К) при 623 К, метал отриманий з Fe_2O_3 при 1073 К:
1 – 1 % KCl, 2 – без добавки, 3 – 1 % LiCl

Негативний ефект посилювався зі збільшенням кількості добавки в шихті (рис. 8).

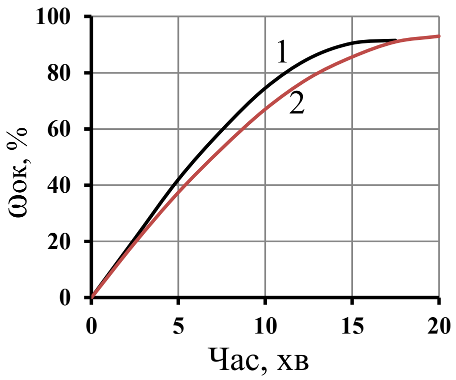


Рис. 8. Вплив кількості каталізатора на окислюваність заліза при 332 К, метал отриманий з Fe_2O_3 при 1073 К: 1 – 3 % KCl, 2 – 1 % KCl

Для зниження окислюваності металевого продукту було використано змінну ЕМП промислової частоти. Воно накладалося на систему, що реагує, як у процесі відновлення, так і в ході окислення отриманого заліза.

В обох випадках спостерігалося зниження швидкості взаємодії металу з киснем повітря та зменшенням граничного $\omega_{ОК.}$ (рис. 1, 2).

Однак ці ефекти для порошкових матеріалів були порівняно невеликими: відносне зменшення кінцевого значення $\omega_{ок.}$ складає 10-15 %. Електромагнітні впливи протягом усього досліду показали, що мало відрізняються (рис. 1, 2).

Подібна картина мала місце при добавках каталізатора KCl в шихту. Змінне поле знижувало окислюваність заліза (рис.3, 4), проте величина граничного значення $\omega_{ОК.}$ залишалася більшою, ніж у дослідах без добавок.

Встановлені закономірності для залізорудних порошків повторилися для руди фракції 0,5-2,5 мм. Разом з тим ефективність накладання ЕМП, особливо при невисоких температурах, на окислення заліза виявилася більшою, ніж у дослідах з порошковими матеріалами. Так залізо, відновлене при 873 К в умовах енергетичних впливів, з киснем повітря при 373 К практично не взаємодіяло (рис. 9). Аналогічна картина спостерігалася в процесі окислення заліза при 473 К, якщо воно було отримано при 973 К; а у разі відновлення при 873 К кінцеве значення $\omega_{ОК.}$ зменшується на ~1/3 (рис. 10).

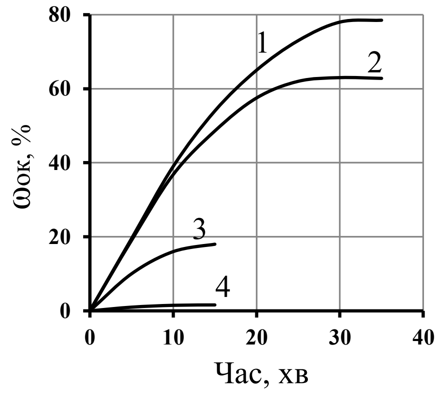


Рис. 9. Вплив ЕМП на окислюваність заліза при 373 К, залізо отримано з руди при 773 і 873 К: 1,3 – поза полем; 2,4 – у полі; 1,2 – 773 К; 3,4 – 873 К

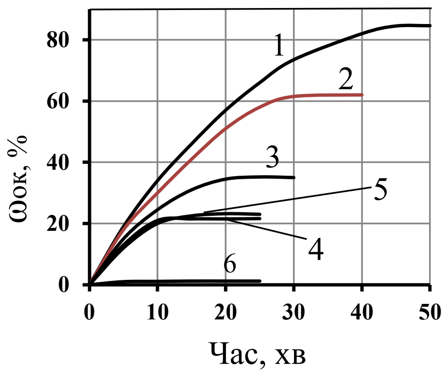


Рис. 10. Вплив ЕМП на окислюваність заліза при 473 К, залізо отримано з руди при 773-973 К: 1,3,4 – поза полем; 2,5,6 – у полі; 1,2 – 773 К; 3,5 – 873 К; 4,6 – 973 К

Підвищення температури окислення до 573-673 К знижувало результати впливу поля (рис. 11 та табл. 1).

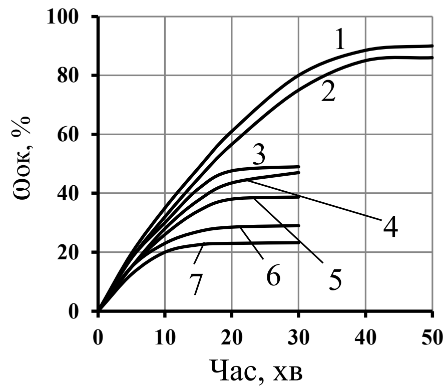


Рис. 11. Вплив ЕМП на окислюваність заліза за 573 К, залізо отримано з руди при 773 – 973 К: 1,3,4,7 – поза полем; 2,5,6 – у полі; 1,2 – 773 К; 3,5 – 873 К; 4,6 – 973 К; 7 – 1 година в Ar

Перевірка показала, що ЕМП, накладене на процес відновлення, впливає на окисленість металевого продукту головним чином на завершальному етапі реакції. Включення поля при досягненні $\omega_{вид.}$ = 60 % уповільнювало подальше окислення заліза, хоча й слабше, ніж у разі більш раннього накладання поля, але протягом всього досліду (табл. 2).

Таблиця 1 - Вплив ЕМП на окислюваність заліза при 673 К (залізо отримано з руди при 773-973 К)

Час окислення, хв	Ступінь окислення заліза (%) при різних впливах на систему					
	поза полем	у полі	поза полем	у полі	поза полем	у полі
	773 К		873 К		973 К	
10	36,5	36	35,8	35,5	34,5	30
20	61,5	60,8	59,5	58,5	57,5	54
30	79	78,2	77	76	74,5	70
40	89,4	88,4	85	84	82,4	78,6
45	92,6	91,4	87	86	84	80
50	94,6	93,6	88	87	84,5	
55	95,6	94,6	88,5	87,5		

Таблиця 2 - Вплив тривалості електромагнітного впливу на окислюваність заліза при 673 К (метал отримано з руди при 973 К)

Час окислення, хв	Ступінь окислення заліза (%) при різних впливах на систему				
	поза полем	у полі	поле увімкнене при $\omega_{ок.}$=20 %	поле увімкнене при $\omega_{ок.}$=40 %	поле увімкнене при $\omega_{ок.}$=60 %
10	35	30	31,5	32,5	33,5
20	60	54,5	55	56,5	58
30	77	71,5	72	73,5	75
40	85	79	80	81,8	83
50	87	80	81	82,5	84
55	87,2	80,3	81,2	83,0	84,3

Цікаві дані були отримані при введенні у відновлювану шихту LiCl. Хлорид літію суттєво гальмує відновлення оксидів заліза газами. Однак, окислюваність металевого продукту також суттєво зменшувалася, що знайшло відображення у значному зростанні температури початку окислення, зниженні швидкості процесу та граничного значення $\omega_{ок,}$ (рис. 6 та 7). У той же час добавки LiCl прискорюють вуглецевотермічне та комплексне відновлення заліза. Це дозволило припустити, що використання хлориду літію у процесах за участю вуглецю дає ефект інтенсифікації без істотного збільшення окислюваності заліза.

Дійсно, перевірка показала, що залізо, отримане комплексним відновленням магнетитового концентрату в присутності 3 % LiCl при 1173 К починає взаємодіяти з киснем повітря при температурі, близької до дослідів, що спостерігалося без добавки. Введення в шихту 3 % KCl помітно знижує температуру початку окислення (до 593 К).

За літературними даними [20], причини високої окисленості та пірофорності залізних порошків та губки вивчені недостатньо. Однак, безсумнівно, що пірофорність заліза вирішальною мірою визначається його будовою, насамперед, дисперсністю частинок і дефектністю кристалічної решітки. Саме тому залізо, отримане при низькотемпературному відновленні, коли процеси «збиральної» кристалізації не мають суттєвого розвитку, а решітка характеризується невпорядкованістю, проявляється підвищена схильність до окислення.

На основі отриманих результатів досліджень та літературних відомостей можна представити механізм впливу енергетичних та хіміко-каталітичних впливів на окислення свіже відновленого заліза. Окислення заліза [21] супроводжується збільшенням об'єму кристалічної фази. Внаслідок цього оксид росте на поверхні металу у вигляді щільного, непористого, покривного шару. Внутрішньодифузійний транспорт газоподібного кисню в реакційній зоні дуже утруднений і в умовах неушкодженої оксидної плівки процес здійснюється, головним чином, через дифузію іонів заліза і кисню через кристалічну решітку оксиду.

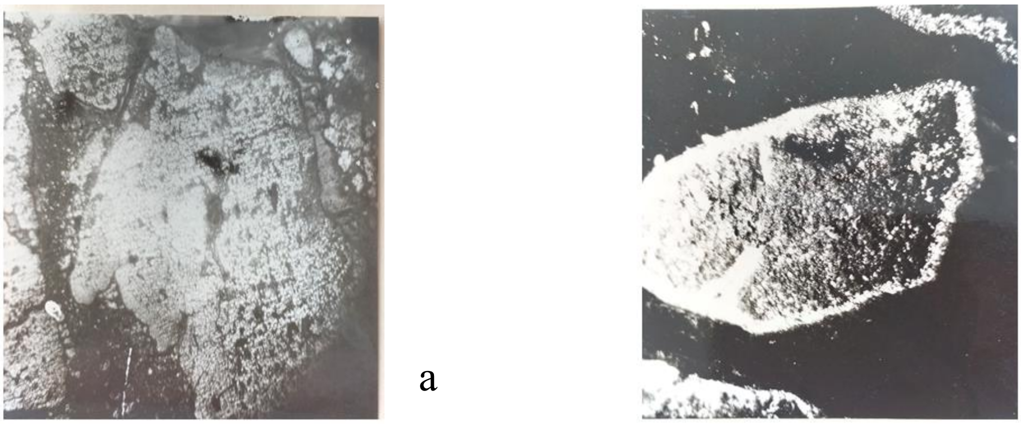
Встановлено [22,21], що структурна картина окислення заліза добре узгоджується з особливостями діаграми Fe-O, швидкість утворення окремих оксидних верств лімітується твердофазною дифузією іонів. У решітці вюститу визначальна роль належить переміщенню катіонів заліза, чому сприяє дірчаста природа FeO. У шарі Fe_3O_4 також переважає дифузія заліза, що протікає по міжвузлях і вакансіях, що завжди є в решітці шпінелі [22], тут дифузія іонів заліза зустрічає значно більший опір, ніж у шарі FeO. У формуванні зовнішнього шару – Fe_2O_3, визначальна роль, вочевидь, належить іонам кисню, які переміщуються через аніонні вакансії кристалічної решітки.

Механізм окислення відновленого заліза значною мірою визначено в області високих температур. Нижче 843 К багато залишається неясним [22], хоча саме ці температури становлять найбільший інтерес з точки зору окислюваності та пірофорності заліза. Можна обґрунтовано стверджувати, що зростання температури відновлення збільшує (за інших рівних умов) температуру початку окислення, знижує його швидкість і граничну $\omega_{ОК.}$, перш за все в результаті розвитку «збиральної кристалізації» в процесі відновлення та рекристалізації вже утворених твердих фаз. Підвищення температури окислення, навпаки, прискорює реакцію та збільшує кінцеву $\omega_{ОК.}$. Це зумовлено, головним чином, зростанням швидкості твердофазної дифузії та полегшенням кристалохімічних перетворень загалом.

Окислюваність металевого продукту, природно, залежить від виду використовуваних шихтових матеріалів та способу відновлення. Так залізо, отримане з порошкових та зернистих шихт за допомогою газів, знаходиться у неоднакових умовах. У першому випадку гірша газопроникність зразка в цілому, а в другому – утруднюється доступ кисню всередину окремих зерен. Це визначає більш глибоке окислення залізного порошку і пробуджує деякі особливості впливу змінного ЕМП на кінетику процесу.

Зменшення окислюваності заліза при різних варіантах накладання поля пов'язане з розглянутим раніше зростанням рухливості іонів кристалічної решітки, який обумовлений явищем магнітострикції. Висока рухливість іонів при енергетичних впливах у процесі відновлення сприяє кристалохімічному перетворенню в системі Fe-O, забезпечує успішний перебіг «збиральної кристалізації» нових фаз, знижуючи дисперсність металевого продукту та сприяючи упорядкуванню решітки. Вплив поля в ході окислення завдяки тому ж ефекту сприяє подальшому впорядкуванню кристалічної решітки заліза та його рекристалізації. Зазначені явища призводять до зниження окислюваності металу і при накладенні поля в ході всього досліду, що охоплює відновлювальний та окислювальний періоди.

Вочевидь, процеси «збиральної кристалізації» та рекристалізації розвиваються переважно в межах окремих частинок порошку, не знижуючи помітно газопроникності його в цілому. Тому вплив поля в даному випадку порівняно невеликий. Ці ж процеси, протікаючи у межах щодо великих зерен руди, забезпечують хороший захист кожного з них від окислення, зумовлюючи високу ефективність ЕМП (рис. 12, а і б).



а б

Рис. 12. Діаметральний розріз окисленої при 473 К зерен багатої руди, попередньо відновленої при 873 К: а) поза магнітним полем;
б) в магнітному полі; білі ділянки – Fe_2O_3, темні – Fe_3O_4

Вплив добавок солей лужних металів на окислюваність заліза може бути пов'язаний з їх впливом на відновлювальний процес. Зокрема, хлорид калію сприяє кристалохімічним перетворенням оксидів заліза. Тому процес розвивається за участю великої кількості зародків нової фази, що одночасно утворилися. Отримане в таких умовах залізо характеризується високою дисперсністю та, відповідно, окислюваністю. Слід також мати на увазі, що дефектність кристалічних решіток оксидів, обумовлена впровадженням іонів K^+, може певною мірою зберігатися в металевому продукті, повідомляючи йому підвищену реакційну здатність у взаємодії з воднем. Зазначений ефект зростає зі збільшенням кількості KCl у шихті.

Інгібуючи дії хлориду літію в процесі окислення також може бути зумовлена його впливом на кристалохімічні перетворення при відновленні. Як зазначалося, LiCl ускладнює ланку хімічної реакції відновлення. Тому процес починається з обмеженою кількістю зародків нової фази. Металевий продукт утворюється порівняно великодисперсним і пасивнішим щодо кисню. Дефектність кристалічної решітки заліза, мабуть, невелика і, ймовірно, не грає вирішальної ролі.

Вочевидь, подібний характер впливу LiCl на окислюваність заліза має місце у відновленні залізорудних матеріалів за участю вуглецю, хоча в цьому випадку ефективність добавки не висока, проти за відновленням газами. Однак безперечною перевагою є те, що одночасно відбувається інтенсифікація процесу.

Слід зазначити, що не виключена можливість впливу KCl та LiCl у ході самого окислення. Невеликі залишкові кількості добавок можуть впроваджуватися в решітку оксиду, що утворюється, змінюючи при цьому швидкість процесу. Зокрема Li^+ може заповнювати катіонні вакансії та впроваджуватися у міжвузлі, ускладнюючи дифузію іонів заліза у процес окислення загалом; K^+, навпаки, викликає утворення нових вакансій, полегшуючи окислення [22].

Висновки

ЕМП, що накладене на процес відновлення, впливає на окисленість металевого продукту головним чином на завершальному етапі реакції.

Результати дослідження показали, що відновлення при 873 К і більш високих температурах забезпечує отримання металізованого продукту, який нижче 473 К практично не реагує з киснем повітря.

Введення в шихту KCl та інших інтенсифікаторів відновлювального процесу змінює T_{OK}, у порівняно вузьких межах.

Позитивний вплив ЕМП при використанні зернистої шихти сильніший, ніж при відновленні порошків.

Окислюваність заліза можна регулювати варіюванням температури відновлення та складом газового потоку.

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Obtaining sponge iron in a rotary shaft furnace using Inmetco technology with combined sintering and metallisation processes

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Отримання губчастого заліза в обертовій шахтній печі за технологією Inmetco з комбінованими процесами спікання та металізації

Анотація. *З численних процесів без коксової металургії, виробництво губчастого заліза зараз досягло свого найбільшого промислового розвитку. Причиною цього розвитку стала можливість організувати виробництво високоякісного металу за такою схемою: технологія переробки дрібнодисперсних відходів доменного та сталеплавильного виробництва в рудно-вугільні композитні котуни, їх кальцинація та металізація на кільцевій камері ПВП; використання цієї технології в процесах INMETCO, FastMet та DRYIron. У цій статті обґрунтовано умови отримання губчастого заліза в ПВП-печі (роторній подовій печі). Метою цієї роботи є експериментальне дослідження процесу отримання губчастого заліза шляхом поєднання спікання та металізації рудно-вугільних композитних котунів у роторній подовій печі. Методи дослідження: хімічний аналіз отриманих котунів, визначення загального та металевого заліза, залишкового вуглецю, шлакоутворюючих компонентів. Матеріальний та тепловий баланс процесу металізації, розрахунок питомої витрати енергії та визначення втрат тепла по зонах печі.*
Ключові слова: *дрібнодисперсні відходи, рудно-вугільні композити, піч ПВП, губчасте залізо.*

Abstract. *Of the numerous processes without coke metallurgy, sponge iron production has now reached its greatest industrial development. The reason for this development was the possibility to organise the production of high-quality metal according to the following scheme: technology for processing finely dispersed waste from blast furnace and steelmaking production into ore-coal composite pellets, their calcination and metallisation on a PVP ring chamber calciner; use of this technology in the INMETCO, FastMet, and DRYIron processes. This article substantiates the conditions for obtaining sponge iron in a PVP furnace (rotary hearth furnace). The aim of this work is to experimentally study the process of obtaining sponge iron by combining sintering and metallisation of ore-coal composite pellets in a rotary hearth furnace. Research methods: chemical analysis of the obtained pellets, determination of total and metallic iron, residual carbon, slag-forming components. Material and heat balance of the metallisation process, calculation of specific energy consumption and determination of heat losses by furnace zones.*
Keywords: *finely dispersed waste, ore-coal composites, PVP furnace, sponge iron.*

1. Introduction

The blast furnace (BF) continues to be the main reactor for the production of iron due to its high productivity and thermal efficiency. However, it requires a minimum amount of coke and a high-quality iron ore charge. The presence of coking coal, coke plant, sintering plant is mandatory, which is a major problem in terms of cost and environmental pollution [1,2]. The total CO2 emission from the blast furnace is about 2 tons of CO2/ton of hot metal. Another important aspect is the use of fines generated during the mining/enrichment of iron ore and coal. All these factors have led to the development of alternative routes for the production of iron. Rotary hearth furnace (RHF) processes are one such category of alternative routes for the production of iron that has recently attracted significant attention [3-6].

Presently, most of the iron is produced through blastfurnace route, which requires metallurgical coke. Thedepletion of coking coal reserves and growing environ-mental concerns have motivated researchers to search forcoke-free iron ore reduction processes leading to alterna-tive routes of iron making. One class of methods is directedat the production of iron nuggets/sponge using iron orefines and non-coking coal fines in the form of pellets. Thesponge/nuggets are then smelted separately. The otherclass of methods directly produces molten iron. Severalvariants of RHF technologies aimed at sponge/nuggetsproduction have evolved such as Inmetco, Fastmet,Fastmelt, and ITmk3. It is claimed that these processesreduce CO2emission, although specific data on cases arelacking.RHF process is a coal-based direct reduction processthat uses iron ore fines and non-coking coal fines toproduce premium-quality sponge iron or iron nuggets

The globalisation of the world economy has had a major impact on the ferrous metallurgy industry and continues to influence this sector. This industry is undergoing significant structural transformation. During the 1990s and 2000s, these changes were characterised by the development of new concepts in steel production (e.g. mini-electric steelworks, new concepts for electric arc furnaces, new casting technologies and direct reduction or recovery smelting technologies).

For the first time on an industrial scale, INMETCO introduced a new continuous metallisation process [2] for RHF iron ore pellets. The basics of the RHF rotary hearth furnace process are well known: raw pellets are obtained from a charge consisting of iron-bearing pellets and carbon in appropriate proportions for their metallisation [2-5].

A distinctive feature of the process is the loading of a thin layer of pellets onto the furnace floor, which are heated by radiation from a high-temperature torch burning directly above the layer. This ensures that the pellets are heated and almost completely restored within 6-8 minutes. The rotary furnace can be divided into three zones. In the first zone, the pellets are heated to 980-1000°C for 1.5-2.0 minutes by burning the volatiles released from the coal. In the second zone, at 1150°C, a noticeable reduction reaction takes place. The furnace atmosphere in this zone is oxidising with respect to iron, but the carbon monoxide released from the pellets protects the reduced iron from oxidation. In the third zone, at 1250-1320°C, the reduction is completed. The atmosphere in this zone corresponds to the equilibrium for the Fe-FeO system. At high temperatures, the reduced iron particles sinter, which leads to volumetric shrinkage of the pellets and their compaction.

The heat for reduction in the second and third zones is released during the combustion of CO. In addition, natural gas or fuel oil. The implementation of the counterflow principle of heating gas and pellets ensures full fuel utilisation. The degree of metallisation of sponge iron is over 90%. A change in the residual carbon content in the metallised product from 1.5% to 10% is an integral characteristic of this process.

Loading the metallised product with a temperature of at least 860°C into the smelting unit will significantly reduce the consumption of electricity, electrodes and refractories. The research results below can be used as initial data for designing a section for the production of metallised raw materials as part of a mini-plant [7-15].

2. Experiments in a tube furnace.

The research was conducted in two stages. The main elements of the technology were tested in the first stage in a laboratory tube furnace, and in the second stage in a semi-industrial furnace.

The following materials were used for testing in the tube furnace:

Name	Fe_{tot}	SiO_2	CaO	Al_2O_3	MgO	S
Magnetite concentrate	64,1	3,2	1,9	0,8	1,1	0,01
Bentonite	3,1	64,5	1,0	17,2	3,2	<0,1
Ash	13,5	35,7	20,1	10,2	3,3	-

Name	C	S	V	A	H_2O
Petroleum coke	94,8	2,4	4,8	0,4	11,0
Coal	48,6	0,3	37,2	14,2	5,5

The granulometric composition of raw materials and fuel was as follows:

% fraction, mm	+1,0	+0,5	0,1	0,071	-0,071
Magnetite concentrate	0	0,2	0,2	4,6	95
Petroleum coke	0	12,2	65,9	13,6	8,3
Coal with volatile content	0,2	9,3	30,2	22,8	37,5

three batches were studied, from which raw pellets were obtained and then reduced in a tube furnace.

Composition of raw pellets, %

Batch 1: 73% concentrate, 26% coal, 1% bentonite

Charge 2: 85% concentrate, 14% coal, 1% bentonite Charge 3: 80% concentrate, 9.5% coal, 9.5% petroleum coke, 1% bentonite

After high-temperature reduction, metallised pellets with the following compos

ition were obtained:

Burning		Composition of metallised pellets, %								
t^0C	τ, min	Charge	C	S	Fe_{tot}	Fe_{met}	Al_2O_3	CaO	MgO	SiO_2
1225	15,0	1	3,3	0,1	81,1	95,6	1,7	3,5	1,6	8,5
1280	10,0	1	0,98	0,1	83,0	94,0	1,7	3,6	1,6	8,4
1225	15,0	2	2,0	0,4	84,5	90,2	1,2	2,1	1,3	5,6
1225	10,0	3	1,9	0,4	83,3	96,2	1,3	2,6	1,4	6,8

The experiments showed that it's basically possible to get metallised pellets from a mix of iron ore concentrate and carbonaceous materials of different compositions, including iron-containing waste.

3. Experiments to determine the technical and economic indicators of the Inmetco process were carried out using a semi-industrial plant.

The following materials were used for these experiments: iron ore concentrate: Fetot – 68,8%; S – 0,04%; fractions – 0,071 mm - 95%; coal: C -51,3%; S – 0,83%; ash – 9,0%; volatile matter – 39,7%; in coal ash: SiO_2 -62,5%; A12O3 - 28.6%; CaO - 4.4%; MgO - 00.33%; fractions - 0.050 mm - 21.8%; +0.050 mm - 78.2%; bentonite: FeOb - 3.1%; SiO2 - 064.5%; Al2O3 - 017.2%. Raw pellets: moisture content - 10.3%; carbon content - 19.3%; pellet size - 8 - 10 mm, compressive strength - 1.4 kg/p.

The experiment lasted 9 hours, of which 4 hours were identified as having the best performance. The results of the experiment are shown in Table 1, and the material balance is shown in Table 2.

Table 2 Indicators of the metallisation process on a semi-industrial installation

Indicator name	Average for 9 hours of work	Best 4 hours of work.
Effective bed area, m2	5,723	5,723
Carbon content in raw pellets, %	19,3	19,3
Loading rate, t/hour	5,0	5,0
Temperature, °C		
Zone 1	1225	1225
Zone 2	1335	1335
Layer height, m	0,0172	0,0172
Specific productivity, t/m2hour	0,422	0,422
Chemical composition of the product, %		
Sample No. 4	92,8	93,4
Degree of metallisation, %	5,8	5,6
Residual carbon content, %		
Sample No. 5	87,8	89,1
Degree of metallisation, %	4,4	4,5
Residual carbon content, %	4,27	4,26

Table 3 Material balance of the metallisation process at a semi-industrial facility.

Indicator name	Average for 9 hours of work	Best 4 hours of work.
Zone 1		
- natural gas, m3/hour	143	139
- combustion air, m3/hour	2438	2352
Zone 2		
- natural gas, m3/hour	137	140
- coal on the burner, kg/hour	457	457
- combustion air, m3/hour	4041	4715
- air for coal transportation, m3/hour	292	292
Raw pellets	4,54	4,54
Material consumption, t/hour		
concentrate	2,994	2,994
coal	0,953	0,953
bentonite	0,018	0,018
water	0,468	0,468
Product output t/huor	2,6	2,6

Table 3 Energy consumption

Indicator name	Average for 9 hours of work		Best 4 hours of work.	
		%	$\frac{G_{кал}}{час}$	%
Natural gas:				
Zone 1	1,17	9,7	1,14	9,5
Zone 2	1,12	9,3	1,14	9,5
Coal				
Burners	3,24	27,0	3,24	27,0
Pellets	6,49	54,0	6,85	54,0
total	12,02	100,0	12,01	100,0

Table 4 Energy expenditure with and without carbon accounting

Metallised product output	0,574 т/т$_{raw\ pellet}$
Specific energy consumption	G кал
Amount of energy from carbon remaining in the product	4,62 $G_{calories}/t_{product}$
Energy consumption minus residual carbon	0,35 $G_{calories}/t_{product}$
Heat losses:	$G_{calories}/t_{product}$
with cooling water during unloading	4,27 $G_{calories}/t_{product}$/0,23
through the furnace walls	0,27
refrigerators	$8,8 \times 10^{-6}$
- with exhaust gases	1,34
-unburned components of exhaust gas	0,45

The advantages of using sponge iron in a blast furnace are reduced coke consumption (about 7% for every 10% of metallic iron in the charge) and increased productivity (about 8% for every 10% of metallic iron in the charge). The blast furnace is less demanding in terms of slag-forming content and degree of metallisation, but strict control of the content of alkalis, zinc and other impurities in the charge is necessary.

When using sponge iron in electric arc furnaces, higher requirements are imposed on it. The degree of metallisation, the amount of slag-forming substances, the sulphur content, density and strength are critical factors that determine the productivity and quality of the metal. Accordingly, good results can be achieved by using iron-containing materials with a low content of slag-forming agents, low-ash and low-sulphur coal and, as a result, sponge iron with a high degree of metallisation.

Table 5 shows the costs for the production of sponge iron using Inmetco technology for conditions in the USA.

Sponge iron produced in a rotary hearth furnace using Inmetco technology is the cheapest. Production costs for a plant with a capacity of 500,000 tonnes per year of sponge iron are approximately 60 USD per tonne.

As a rule, in order to save energy costs, rotary hearth furnaces are built at mini-plants or full-cycle metallurgical plants. The capacity of one furnace is up to 600,000 tonnes of sponge iron per year.

Table 5 Characteristics of raw materials and sponge iron for some processes

Characteristics of materials	Blast furnace Electric arc furnace Blast furnace Electric arc furnace	Blast furnace Electric arc furnace Blast furnace Electric arc furnace
Iron ore concentrate, iron ore by SiO_2 content (%)	<6	<3
Coal ash	<12	<8
Arrivals (Na_2O_3)	<3 kg/m_{Fe}	-
Arrivals of zinc	<2 kg/m_{Fe}	-
Pellet size, mm	16-22	8-14
Degree of metallisation, %	85-82	>90
Residual carbon content, %	4-7	1,5-3,0
Compressive strength, kg/pellet	>250	>200

Thus, the production of sponge iron in a rotary hearth furnace using Inmetco technology is the most efficient way to obtain high-metal pellets from finely ground concentrates and various carbonaceous reducing agents. Sponge iron produced using this technology is a source of primary metal for steelmaking.

Table 6 Costs for sponge iron production using Inmetco technology

Production costs	Units of measurement	Consumption kg/t
Raw materials:		
iron-containing	kg	1335
coal	kg	410
bentonite	kg	5
organic binder	kg	5
Total: raw materials		
Energy costs:		
electricity	kW · hour	65
natural gas	m^3	60
nitrogen	m^3	10
water	t	0,30
Other expenses		
Expenses	USD	
Repairs and spare parts	USD	

Conclusions

Thus, the production of sponge iron in a rotary hearth furnace using Inmetco technology is the most effective way to obtain high-metal pellets from finely ground concentrates and various carbonaceous reducing agents. Sponge iron produced using this technology is a source of primary metal for steelmaking in the smelting of low-carbon steels and alloys. Due to the high residual carbon content in sponge iron, there is no need to add carbon-containing materials in the production of high-carbon steels.

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Місце винахідництва як складової інтелектуально–фахового потенціалу науковців у вдосконаленні промислових технологій

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The place of invention as a component of the intellectual and professional potential of scientists in improving industrial technologies

Анотація. *Сучасний етап розвитку науки і технологій характеризується зростаючою потребою у пошуку нових рішень, що забезпечують підвищення ефективності промислового виробництва, його екологічність, енергоощадність, раціональне використання ресурсів мінеральної сировини та конкурентоспроможність. У цьому контексті особливого значення набуває винахідництво як прояв інтелектуально-фахового потенціалу науковців, здатного трансформувати фундаментальні знання у прикладні інновації, що безпосередньо впливають на вдосконалення сучасних промислових технологій. Винахідництво не є ізольованим процесом – воно формується в системі взаємодії науково-освітнього, виробничо-технологічного та соціально-економічного середовищ. Його розвиток зумовлений низкою умов - від наявності сприятливої нормативно-правової та інституційної бази до стимулювання процесу на всіх етапах його життєвого циклу. Народжуватися, як форма творчої діяльності, винахідництво може там, де ці складові взаємодіють у середовищі, якщо воно стає фактором стимулювання його виникнення, сприяння розвитку та подальшої реалізації – в освітньо-науковому просторі, виробничо-технологічному середовищі та інноваційно-привабливому економічному полі. Обґрунтовано доцільність визначення фахово-професійної складової потенціалу особистості як п****осередника між знаннями та практикою****, використання корисних властивостей якої сприяє перетворюванню інтелекту та креативності на конкретні результати професійно - творчої діяльності особистості. Як спосіб самовираження, здатність людини до винахідництва в своїй діяльності не з'являється сама по собі, її можна цілеспрямовано розвинути з використанням наступних засобів:* ***освітніх, практичних, психологічних та соціально-професійних.*** *Показано, що професійна складова займає рівноправне місце поряд із розумовою та емоційною складовими, адже саме вона забезпечує практичне застосування двох інших у сфері трудової діяльності та самореалізації в науковій діяльності. В дослідженні використано аналітико-оглядові методи дослідження умов розвитку винахідництва в напрямку удосконалення металургійних процесів, з акцентуванням їх фізико-хімічної сутності та спрямованості. Показано, що нівелювання ролі особливостей трансформації властивостей фізико-хімічного потенціалу об'єкту/процесу дослідження знижує як наукову цінність, так і не сприяє визначенню спектру реальних функціональних можливостей їх перетворення. Метою дослідження є обґрунтування факторів впливу, зовнішніх та внутрішніх за походженням, та умов, що сприяють розвитку винахідництва як творчої форми діяльності науковця з визначенням ключових складових потенціалу особистості, що, в свою чергу, є умовою розробки інноваційних, конкурентоспроможних рішень. Останні спроможні більш раціонально вирішувати проблеми енергоефективності, збереження ресурсів мінеральної сировини, енергії та суттєвого зменшення втрат корисних властивостей потенціалу навколишнього середовища. Вперше, теоретично обґрунтовано, що фахово-професійна складова (ФПС) є третьою та ключовою складовою потенціалу особистості, поряд із розумовою та емоційною. Існують праці, результати яких, визначені їх авторами, близько окреслюють роль професійного чи фахового потенціалу в структурі особистісного розвитку. Їх підходи, що використано при визначенні складу та ролі факторів впливу, опосередковано, підтверджують вагомість фахового компонента саме як складової, що забезпечує професійну, творчу самореалізацію особистості і у винахідницькій діяльності. Але прямої згадки про модель-тріаду «розумова – емоційна – фахово-професійна» складові інтелекту особистості дослідниками не знайдено. Винахідництво, займаючи центрально-інтегративне місце серед факторів впливу поєднує їх у єдину систему, створює ефект синергічного прискорення розвитку науки й технологій, переводячи інтелектуально - фаховий потенціал суспільства у конкретні інноваційні результати на практиці.*

Ключові слова: *винахідництво, фаховий потенціал, інноваційний результат, фахово-професійна складова, потенціал особистості.*

Abstract. *The current stage of development of science and technology is characterized by a growing need to find new solutions that ensure increased efficiency of industrial production, its environmental friendliness, energy saving, rational use of mineral resources and competitiveness. In this context, invention is of particular importance as a manifestation of the intellectual and professional potential of scientists, capable of transforming fundamental knowledge into applied innovations that directly affect the improvement of modern industrial technologies. Invention is not an isolated process - it is formed in the system of interaction of scientific and educational, production and technological and socio-economic environments. Its development is conditioned by a number of conditions - from the presence of a favorable regulatory and institutional framework to stimulating the process at all stages of its life cycle. Invention, as a form of creative activity, can be born where these components interact in the environment, if it becomes a factor stimulating its emergence, promoting*

development and further implementation - in the educational and scientific space, the production and technological environment, and the innovative and attractive economic field. The expediency of defining the professional component of the potential of the individual as a mediator between knowledge and practice Vanyukov A.A., Kamkina L.V., Myanovskaya Y.V., Kovalyov M.D., Tsibulya E.V., Chumak D.D., the use of useful properties of which contributes to the transformation of intelligence and creativity into specific results of the professional and creative activity of the individual, is substantiated. As a way of self-expression, a person's ability to invent in his activity does not appear by itself, it can be purposefully developed using the following means: educational, practical, psychological and socio-professional. It is shown that the professional component occupies an equal place alongside the mental and emotional components, because it is it that ensures the practical application of the other two in the field of labor activity and self-realization in scientific activity. The study used analytical and survey methods to study the conditions for the development of invention in the direction of improving metallurgical processes, with an emphasis on their physical and chemical nature and orientation. It is shown that leveling the role of the features of the transformation of the properties of the physicochemical potential of the object/process of research reduces both the scientific value and does not contribute to determining the spectrum of real functional possibilities of their transformation. The purpose of the study is to substantiate the factors of influence, external and internal in origin, and the conditions that contribute to the development of invention as a creative form of activity of a scientist with the definition of key components of the potential of the individual, which, in turn, is a condition for the development of innovative, competitive solutions. The latter are able to more rationally solve the problems of energy efficiency, conservation of mineral resources, energy and a significant reduction in the loss of useful properties of the environmental potential. For the first time, it is theoretically substantiated that the professional component is the third and key component of the potential of the individual, along with the mental and emotional. There are works, the results of which, determined by their authors, closely outline the role of professional or professional potential in the structure of personal development. Their approaches, used in determining the composition and role of factors of influence, indirectly confirm the importance of the professional component precisely as a component that ensures professional, creative self-realization of the individual and in inventive activity. But researchers have not found a direct mention of the model-triad "mental - emotional - professional-professional" components of the intelligence of the individual. Invention, occupying a central-integrative place among the factors of influence, combines them into a single system, creates the effect of synergistic acceleration of the development of science and technology, translating the intellectual - professional potential of society into specific innovative results in practice.
Keywords: *ingenuity, professional potential, innovative result, professional component, personal potential.*

Introduction.

The modern development of industrial technologies increasingly depends on the level of intellectual and professional potential of scientists, among the key components of which invention occupies a special place. It acts not only as a tool for generating new ideas, but also as a catalyst for creating innovative technological solutions that can ensure the competitiveness of production in the conditions of the global economy. Inventive activity reflects the synthesis of knowledge, professional competencies and creativity, transforming scientific and technological progress into practical results that contribute to the improvement of industrial processes, increasing the level of rational use of their resource base and reducing the negative impact on the environment.

The process of forming inventive activity occurs within the framework of the complex interaction of the system of the scientific and educational environment, production and technological complexes and socio-economic factors. Education and science provide training of qualified personnel and generation of new knowledge, industry forms a demand for innovative solutions, and socio-economic conditions determine real opportunities for the commercialization of inventions. In this context, the relationship with business is important: it is the business environment that becomes the leading platform for testing, implementing and scaling new technologies, acting as a partner in technology transfer, an investor in innovation and the ultimate beneficiary of the results of inventive activity. At the same time, cooperation between science and business provides a two-way effect: scientists gain access to resources, and enterprises gain access to original solutions, which creates a synergy of intellectual capital development and economic growth.

Thus, the study of the place, role and conditions for the development of invention as a component of the intellectual and professional potential of scientists is an urgent task of modern science and practice. Its results will allow us to determine the optimal mechanisms for integrating scientific and technical creativity into production processes, strengthen the partnership between science and business, and lay the foundation for creating an innovation-oriented model of industrial development.

Analysis of the results of the influence of factors of internal and external origin on the state and role of invention as a factor contributing to the enrichment of scientific knowledge, the development and improvement of metallurgical technologies. The result of using the potential of scientific research, both fundamental and applied, is the development of innovative technologies. An important condition for the effective implementation of their results is inventive activity - a component of the intellectual and professional potential of scientists, which is the basis for the development of effective technological solutions. Invention is also one of the important factors influencing the development of scientific areas and the state of modern industrial technologies. Its place is expedient to define as a transformative link between scientific knowledge and its practical implementation in the form of new technologies, materials, processes or their products. If fundamental science creates knowledge, mainly of a theoretical nature, and the technological factor provides a technical basis, then it is invention that allows this knowledge to take an applied form and launch the mechanism of technological transformation, which is the logical conclusion of the process of integrating science and technology.

Regarding the importance of invention, its role among the factors of development of science and technology, it should be noted that its implementation as a creative process:

- ensures the transformation of intellectual potential into real technological and economic achievements;
- acts as a catalyst for the emergence of a source of synergy between various factors (science ↔ economy ↔ technology ↔ ecology ↔ information), the effects of which contribute to the implementation of processes in a given direction with the expected results;
- creates the basis for the competitiveness of technologies, products of their implementation and sustainable development of society, economic security, sustainable development of production in general.

The primary source of the emergence of invention, with high probability, is the combination of three components of human potential: intellectual (scientific knowledge, creative thinking); professional and technical (mastery of tools, technologies, methods); socio-economic (market needs, challenges of society, limitations of mineral raw materials and energy resources). As a form of creative activity, invention can be born where these components interact in the environment, if it becomes a factor stimulating its emergence, promoting development and implementation - in the educational and scientific space, the production and technological environment and the innovative and economic field.

This creative process, obviously, does not operate in isolation, invention is a node in the system of interaction of influencing factors. Synergy, the source of which is the mutual influence of factors, arises when the action of each factor is enhanced by interaction with others. As a result, positive effects arise that bring the process closer to the expected result. To increase the level of informativeness regarding their relationships, it is advisable to present this process in the form of a chain of positive effects of synergy:

- scientific and educational factor - generates knowledge, forms personnel, creates a theoretical basis for the emergence of invention and becomes the primary source of accumulation of practical skills;
- technological - research factor - provides technical opportunities for the implementation of ideas in the experiment and their implementation in practice;
- economic factor - creates incentives, investments, market demand for innovative technological solutions;
- information factor - accelerates the spread of knowledge, ensures communication and their digital transformation;
- environmental factor - sets criteria for sustainable development, forms new restrictions and priorities for inventions;
- inventive factor - integrates all previous synergy effects, transforming knowledge and needs of the economy into new solutions. The latter, through a reverse impulse, launch another reverse cycle of development - scientific and technological breakthrough. As a result, new science, technologies, and economics are created.

Schematically, the sequence of effects of invention as a creative process can be depicted by the following simplified scheme: “scientific and educational → technological → economic → informational → environmental → inventive”, the implementation of which creates a reverse impulse for the development of all previous ones. Thus, invention occupies a central and integrative place among the factors of influence: it not only combines them into a single system, but also creates the effect of synergistic acceleration of the development of science and technology, translating the intellectual and professional potential of society into specific innovative results. And the main task of the state and the Ukrainian National Office of Intellectual Property and Innovations (UKRNOIVI) in solving this problem is to create institutional tools that will help citizens realize their innovative potential [1]. It also includes the protection of rights to intellectual property objects and promoting the introduction of new technologies into business.

The main directions of scientific and technical development (S&T) of the main branches of industry were formed under the influence of economic, technological, environmental, social and other factors of both internal and external origin. Obviously, they became the source of the formation of their scientific and technical potential. The feedback scheme in the system "influence factors ↔ directions of scientific and technical progress (STP)" in the form of a structural diagram is given in Fig. 1.

Let us analyze in more detail the factors of influence, formed into groups according to the main, specific for them, features, on the current state and prospects for further development of STP using examples in Table 1.

The main feature of the relationship of influencing factors (Table 1) is to determine their mutual influence and integration, which becomes the source of the emergence of innovative technologies - the basis of the economic security of an enterprise, industry, state.

For a more complete understanding of the spectrum of functional purpose of intelligence, determining its capabilities in solving problems of improving technological processes, we will determine the features of its components regarding their rational application.

The mental component, which is manifested in the ability to think, analyze, create, learn, forms the intellectual basis on which a person builds knowledge and makes decisions [4].

The emotional component determines the level of emotional intelligence: the ability to manage one’s own emotions, empathize with others, and build relationships with them [5]. Therefore, it is the basis of social interaction and stress resistance, determining the level of socialization of the individual in society. The professional (professional) component is characterized by the level of integration of acquired knowledge, skills, and experience that a person receives in the process of learning and professional activity. It plays the role of a practical tool that allows mental and emotional resources to be implemented in a specific area – from science and technology to art and enterprise personnel management. Thus, we determine that the professional component (FPS) is the third and key pillar of the individual's potential, along with the mental and emotional – a factor that determines the influence on the formation and its development. A conclusion similar in essence and meaning was indirectly made by the author of study [6].

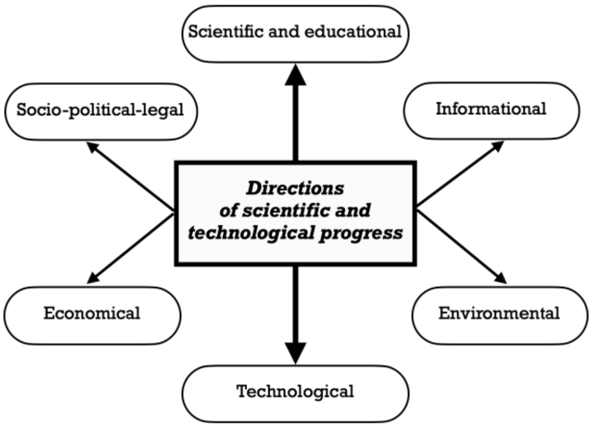

Fig. 1. The main factors influencing the directions of scientific and technological progress

Table 1. Main groups of factors of influence on the development of STP directions

Group of factors	Examples of influence
Economical	Competitive struggle, the need to reduce costs and increase productivity, globalization of markets.
Technological	Breakthroughs in fundamental sciences (physics, chemistry, physical chemistry, computer science), the emergence of new innovative technologies.
Environmental	Strengthening environmental legislation, climate challenges, the need to reduce the carbon footprint.
Social	Growing demands for quality of life, urbanization, demographic changes, labor shortage in high-tech sectors of the economy.
Political and legal	State innovation support programs, international standards, patent law, compliance, trade restrictions, sanctions.
Scientific and educational	Development of STEM education, international scientific cooperation, startup incubators and technology parks [2, 3].
Informational	Rapid exchange of knowledge thanks to the Internet, open access to scientific data, development of collective research platforms.
Human (personal)	Formation of the components of intelligence: mental (IQ), emotional (EQ) and professional (PC - professional component).

In open scientific sources, we were unable to find an exact formulation of such a conclusion, therefore, the definition of the professional component (PCC) as the third, which is probably a key component of the personality potential, along with the mental and emotional, is the result of the authors' analytical research. However, there are works, the results of which closely outline the role of professional or professional potential in the structure of personal development. These approaches used in [6] confirm the importance of the professional component precisely as a component that ensures professional self-realization of the individual, in our opinion, also in inventive activity. But no direct mention of the model-triad "mental - emotional - professional-professional" components of the personality's intelligence was found in this study.

The generalization, integration or synthesis of several theoretical concepts, namely emotional intelligence (EI) as an important component of personal potential, cognitive (mental) resources and professional competence, allows the implementation of these resources in inventive activity. Such concepts are obviously often found in the psychology of professional development, but the issue of determining the independence of the components of the integral potential or their equivalent trinity requires finding compromise solutions through further research.

The place and role of the FPS should be defined as a mediator between knowledge and practice, which transforms intelligence and creativity into specific results of the professional and creative activity of the individual. It is through professional activity that a person contributes to the results of joint work, therefore, the level of qualitative development of the FPS is an indicator of its value for society and an integrator that can combine mental abilities and emotional competence in the ability of a person (team) to act responsibly and effectively.

As a generalized conclusion based on the research results, it should be noted that the mental and emotional components create potential, and the professional component is a path (channel) for the rational and effective realization of the intellectual potential of the individual, and together they make human potential socially and economically significant. Obviously, without this component, a person's professional and emotional maturity will remain unrealized.

Based on the analysis of the essence and role of the main components of the potential of the individual, the place of the professional component along with the mental and emotional components has been determined, which is given in Table 2.

Table 2. The triad of components of the potential of the individual, their essence, role, and relationships

Component of human potential	Essence	Main role
Mental	Knowledge, logic, analytical skills	Provides the ability to think, learn, solve problems, make decisions
Emotional	Empathy, self-control, motivation	Determines the ability to interact with others, manage one's own emotions
Professional	Competencies, practical skills, experience	Implements knowledge and emotional abilities in specific activities, shapes its effectiveness

Thus, based on the data given in the compact scheme - the triad (Table 2), it is necessary to determine that the professional component occupies an equal place along with the mental and emotional components, because it is it that ensures the practical application of the other two in the field of labor activity and self-realization in scientific activity. A visual representation of the triad in the form of a triangle with equal components is given in Fig. 2.

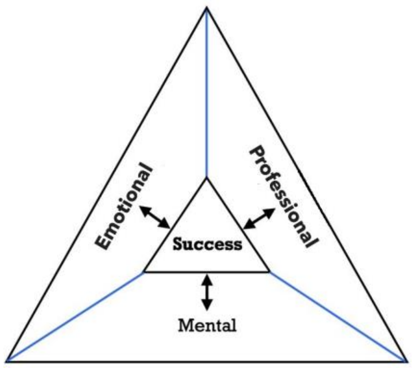

Figure 2 - The triad of components of individual potential as a condition for the success of its implementation

Thus, mental - provides analysis, logic, knowledge, intellectual base; emotional - is responsible for motivation, resistance to stress, interpersonal relationships; professional - practical application of knowledge and emotions in the field of work, self-realization, creating a result. Each component, like the vertex of the triangle, is equally important, therefore, the true power of human intelligence is revealed in the interaction of these three components, which form the components of the intellectual potential of every conscious Ukrainian.

Regarding the importance of emotional intelligence in overcoming the path to "SUCCESS", according to [7], it should be noted that mental development together with emotional (IQ + EQ) is a useful tool for increasing the level of creativity and efficiency of activity as the ability to solve problems in business and generate valuable ideas. Thus, the level of mental intelligence is useful for scientists conducting research, analyzing large arrays of experimental data. Emotional intelligence is responsible for intuition, creativity and empathy. According to the authors, it is more subjective, helps in teamwork when performing interconnected operations, for example, the main stages of metallurgical production.

Analysis of the means that contribute to the formation of a person's intelligence, in the field of his professional activity, the ability to invent, made it possible to determine that it does not appear by itself - it can be purposefully developed using educational, practical, psychological, socio-professional means, through systematic training in logic, critical thinking, methods of scientific knowledge; acquaintance with the history of inventions and their impact on scientific and technological progress. At the same time, the condition for its formation is the analysis of mistakes, successes of inventors with the determination of the sources of their occurrence by developing creativity through modeling, business games, experiments, thinking outside the box. An important means should also be recognized as working in a team with specialists from different fields, scientific directions; participation in competitions, startups, engineering projects, where there is space for practical testing of ideas with the determination of the level of their value and prospects for implementation.

Considering the need for every person in scientific, production and everyday life to rationally use raw materials, fuel, energy, equipment and other resources, let's analyze the reality and feasibility of the slogan we have defined: "You may not become an inventor, but you must become a rationalizer."

The use of certain means in the system "inventor ↔ rationalizer" can be effective for the formation of the ability to invent in the human intellect. At the same time, the slogan "You may not become an inventor, but you must become a rationalizer" has a deep meaning, because invention is the creation of something fundamentally new, which requires a high level of creativity, scientific training, time and appropriate resources. This is the path of units. Rationalization is a creative search for ways to more effectively use existing resources: raw materials, energy, equipment, working time. This is a task that every employee can do, even in everyday life. It is also necessary to note that rationalization is a basic competence of a modern person. It fosters an economical attitude to resources, environmental responsibility and at the same time promotes the development of inventive skills. The one who has learned to rationalize creates the basis for further inventions and discoveries. Therefore, in our opinion, this motto is very apt and timely, because it makes invention a matter of choice, and rationalization a necessity. In a world where resources are limited, the ability to use them rationally should become a habit of every person, regardless of their profession. Invention is a matter of personal choice, and rationalization is a necessity, therefore, in a world where resources are limited, the ability to use them rationally should become a habit of every person, regardless of their profession or field of activity.

In order to determine the differences in the levels of creative activity in the system "inventor → rationalizer → household user", the data of Table 3 were formed, which gives their characteristics with a definition of the role in professional activity.

Table 3. Comparison of the levels of creative activity in the system "inventor → rationalizer → household user"

Level	Characteristic	Role in the activity
Inventor	Creates new fundamentally original ideas, technologies, methods, devices	Provides scientific and technological breakthrough, forms the basis of future industries
Rationalizer	Improves existing tools, processes, and methods	Increases efficiency, resource savings, ease of use
Household user	Uses ready-made solutions in his life and work	Realizes practical benefits, introduces innovations into everyday life

The influence of the factors identified as the main ones is manifested:

- economic - through stimulating the development and implementation of automation, increasing energy efficiency and resource conservation in the implementation of production processes and their digitalization to reduce resource costs for the production of relevant products;
- technological - through innovative breakthroughs opening up new areas, such as additive manufacturing or the use of artificial intelligence;
- environmental - through relevant requirements accelerating the development and application of "clean" technologies and renewable energy.

In modern conditions, the directions of development of STP are becoming more and more dependent on the interests, laws of business development, which as factors of influence, are becoming more and more decisive for its activities. Therefore, one of the effective instruments of influence of state institutions is the creation of conditions that will allow balancing relations in the system "business ↔ STP ↔ state" as conditions for sustainable development of industry, economic security of its industries, enterprises. As a result, business, in the absence of any influence and control from the state institutions of its side, will always defend, regardless of the conditions of development, the position of the state, first of all, its own interests, guided by the laws of business development in a market environment. The motto "your business - your problems" should also have no place in the interaction of the state and business. And fruitful interaction of the state and business in the interests of both parties is an important condition for their economic security and sustainable development in changing environmental conditions.

The results of the systematic analysis of the main directions of scientific and technological progress as a criterion for determining the features and directions of improvement of industrial technologies are given below in Table 4.

In fact, the industrial Internet of Things [7] is the “nervous system” of modern production, which allows obtaining information about the state of machines, energy consumption, product quality and other parameters of processes and mechanisms in real time. To the main areas given in Table 4, it is advisable to add transport and logistics innovations; cybersecurity, the use of functional components of compliance, protection of “know-how” data, etc.

An effective technology is the use of artificial intelligence, created by the efforts of the integrated potential of the individual, to improve the efficiency of existing enterprises. The study [11] identifies areas for the effective implementation of artificial intelligence in various areas: in business, in the financial, banking sectors, industry, marketing, and others. The authors studied examples of the implementation of artificial intelligence technologies by leading world companies in various sectors of the world economy, its various methods and technologies. The high relevance of this area of research was found, especially in times of rapid development of new technologies, when the experience of leading world companies shows that the development of artificial intelligence and its implementation contributes to improving the efficiency of enterprises, accelerating development and increasing profits. It is noted that today AI technologies create new opportunities for enterprises and give them broad powers in various industries, because each process in which AI is implemented optimizes costs, which ultimately has a positive effect on overall financial indicators.

Table 4. Results of the systematic analysis of the main directions of scientific and technological progress

Direction	Essence and examples
Automation and robotization of production	Introduction of industrial robots, automatic lines, CNC systems; use of the Industrial Internet of Things IIoT in production environments [8]. This is a network of industrial sensors and systems that provides data collection, processing and analysis for optimizing industrial processes. The role of IIoT is to create a “smart production” that is based on data and is able to increase energy efficiency, reduce costs, improve quality and safety, and ensure the adaptability of the enterprise to changing conditions. A feasible function of IIoT platforms can be to use data on the physical and chemical characteristics of the relevant technologies as a basis for analytics and rational decision-making.
Digitalization and artificial intelligence	Using large arrays of source data (scientific forecast, experiment, practice), neural networks for process optimization, forecasting and management [9].
Innovative materials, technologies	Development of nanomaterials, composites, biomass-based materials [10]. Development of technologies using useful components of hydrogen potential. Import substitution of resource base materials.
Energy efficiency and resource conservation	Renewable energy: solar and wind installations, regeneration of the useful properties of hydrogen potential, utilization of secondary energy from processes.
Environmentally friendly technologies	Emission reduction CO_2/CO/NO_x/SO_x; recycling of technogenic waste using secondary energy and raw materials - components of their resource potential; closed water circulation systems and low-waste technologies.

Let's move on to the next stage of the study - determining the main components of modern business intelligence, their detailed consideration and establishing their impact on its development. It, as a potential of useful properties, is obviously formed by integrating the following components, which it is advisable to consider in the following, interrelated planes:

- human intelligence (personal) is formed from knowledge, experience, creativity, professional competence of personnel and is determined by the ability to make rational decisions, generate innovative ideas, form corporate ethics, culture;
- organizational intelligence forms management systems, business processes, corporate standards, patents, knowledge bases, brands, which are characterized by stability, even when changing the personnel of the company/enterprise.
- information and technological intelligence forms analytical systems, information resources, databases, creates innovative technologies, and also determines the most effective methods to support decision-making;
- analytical intelligence allows businesses to convert input data into knowledge and make strategic decisions.

As for any type of human activity, it is advisable to consider human intelligence as the most important in business. It is people who create innovative technologies through inventive activity, form business models, determine strategies and tactics for further activity. The most modern information systems remain tools, and their value is manifested only through a person's ability to effectively apply them.

Human intelligence or personal intelligence in the business environment ensures the rational use of its useful properties in solving the following tasks:

- strategic management, which includes setting goals, determining ways to achieve them using competitive advantages, developing appropriate business models;
- innovative development through the creation of new products, services, technologies, searching for non-standard solutions to current business problems;
- adaptation to changes through rapid response to crises that differ in their causes, scale and consequences of their implementation, as well as crises related to production, sales of products, finances and management;
- knowledge management to transform experience

into corporate capital;

- communication and leadership, which includes team building, motivation, and interaction with the external environment.

Thus, the above-defined triad of components of the potential of the individual is the basis, and the components of the intelligence of modern business, when examined in detail, are its derived components of the business, the role and key tasks of which are likely to be determined by the conditions of development, the needs and goals of the business in a competitive economic environment.

Analytical capabilities are identified as an important component of business intelligence, they integrate all the others, transforming information into knowledge, which, in the future, are used in justifying and making strategic decisions regarding the directions of business development: strategic planning, forecasting, assessment of conditions and consequences of the implementation of risks [12].

Main areas of activity, tasks, methods of achieving goals in the metallurgical business. Business relations with state institutions, society, attitude to the resource base of raw materials and energy in wartime are important issues that, by determining the main directions of scientific and technological progress, contribute to the economic security of the enterprise, industry, and state. Generalized data on the main directions of activity of t*he metallurgical business in wartime*, including tasks, methods, and interaction with the external environment, are given below.

The main types of production activities of a business of metallurgical origin should include: production - smelting of pig iron, steel, ferroalloys, rolled products, pipe products; innovation - search for alternative fuels (hydrogen, biocarbon), development of electrometallurgy, digitalization of processes; export - ensuring supplies to foreign markets despite restrictions and changes in logistics conditions; energy - reducing consumption of gas, coal (carbon footprint), electricity; use of energy generated by own generation (hydrogen, wind, sun, water, nuclear energy); social - support for personnel, participation in the reconstruction of the country, preservation of jobs; defense - production of special products for the needs of the Armed Forces of Ukraine (armored steel, elements of fortifications and other structures).

The main tasks of business as factors of its further development, in modern conditions, are:

- stabilization of production in conditions of destruction and supply disruptions;
- diversification of the raw material base (alternative suppliers, use of scrap);
- minimization of energy consumption and increase of energy efficiency;
- preservation of competitiveness of products in European and world markets;
- protection of ecology and fulfillment of requirements of the EU "green deal" (CBAM - Carbon Border Adjustment Mechanism);
- integration into European and global supply chains.

The results of Ukraine's interaction with the European Bank for Reconstruction and Development (EBRD), presented in [13], indicate the gradual and continuous development and deepening of these relations, which are important for the Ukrainian economy.

The most effective in terms of results are the following methods and methods of achieving them in modern conditions: *technological* (transition to electric steelmaking and induction furnaces; increasing the share of scrap metal in the charge; use of pulverized coal fuel (PCF), biochar, hydrogen); *organizational* (creation of reserve routes for the supply of mineral raw materials, fuel and electricity), transition to technologically flexible production (short batches, adaptation to the customer); *economic* (attraction of investments from the EBRD; public-private partnership programs; insurance of wartime risks, etc., which require further justification); *social* (safety programs for personnel; relocation of enterprises or parts of production; humanitarian and defense assistance).

The development of a network of small metallurgical plants that will operate with minimal material, energy and environmental costs as a solution to restore the economy of Ukraine, as indicated by the authors [14], is debatable in our opinion. The potential and certain advantages of metallurgical plants have not yet been exhausted. The path to their restoration is the improvement of existing ones, the creation of innovative technologies and equipment. By the way, the PRC, as a successful economy that has gone from the expansion of "micro-iron production" to the current state of the main industries as a component of the economy, ignore the irrational, study, improve and use to our conditions - yes.

Let us proceed to consider the process of evolutionary development of metallurgical technologies with the definition of the role of invention in it. Each step of the path of continuous improvement of technologies was based on the use of new solutions for the use of oxygen and stabilization of hydro-gas-dynamic processes in the converter bath; regulation of blast and slag melting modes, the use of innovative refractories; vacuum steel processing, continuous casting of billets and, currently, the use of hydrogen as a reducing agent and fuel in DR-shaft and electric arc steelmaking furnaces. Solving these problems has determined the main directions of development of ferrous metallurgy, and their consistent implementation will allow to reduce the energy intensity of the process and determine the directions of reducing the consequences of the carbon footprint in the environment [15,16].

Protection and commercialization of innovations at enterprises of relevant industries, including metallurgical, can be effectively carried out by: introducing new procedures for combating violations of intellectual property rights; promoting licensing and technology transfer to industry; developing tools for international patenting of Ukrainian developments. Thus, the state, through UKRNOIVI and other institutions, builds a chain of interconnected elements, promoting its development: education → patenting → protection → commercialization → integration into the EU and world markets. This is a systemic toolkit for realizing the innovative potential of Ukrainians.

As an important conclusion, it is necessary to determine that all technological solutions that contributed to the development and improvement of steel production methods have a physicochemical nature and orientation, which allowed, for approximately 175 years, through the use of components of scientific and technical potential, to be able to produce about 1 billion tons per year of high-quality steel of a wide range of functional purposes in the world.

The optimal direction for the development of ferrous metallurgy processes for most manufacturers in the next 10–15 years in modern conditions may be a hybrid model, based on the maximum modernization of "ferrous" metallurgy (energy saving, dust and gas purification, partial replacement of coke with hydrogen/gas), with the gradual introduction of "green" technologies in individual processes (electrolysis → H_2 → DRI → EDP), with a gradual increase in the share of hydrogen as the energy for its production becomes cheaper. Thus, in the study [16], which was supported by MIT CS3 and ExxonMobil through its membership in MITEI, the author argues that without the introduction of advanced "greening" technologies, the steel sector could significantly reduce the intensity of CO_2 emissions (per unit of production) using existing steel production technologies - by replacing coal with gas and electricity (especially if it is produced from renewable energy sources), using more steel scrap, and implementing measures to improve energy efficiency.

The main results that are directly aimed at reducing the harmful impact of steel production on the environment include:

- reduction of greenhouse gas emissions - transition from coke blast furnaces to electric steelmaking furnaces (ESF) operating on iron ore product of direct iron reduction (DRI) plants;
- reduction of dust emissions and carbon/nitrogen/sulfur oxides by improving gas cleaning systems, developing coke-free processes;
- increasing the level of energy efficiency through heat recovery (use of physical and chemical energy) of waste gases is the introduction of closed water exchange systems.

When justifying real production schemes for the production of ferrous metals, it is necessary, along with the advantages of "green" metallurgy (reduction of CO_2 emissions and other environmental pollutants, compliance with global environmental standards; long-term reduction of dependence on fossil fuels; image and investment attractiveness; technological modernization of production), to take into account its temporary, but real in time, disadvantages and challenges (high cost of switching to hydrogen; technical limitations associated with limited scale of DRI–H_2 production; energy dependence of hydrogen production, which requires huge amounts of "green" electricity (≈3,5–4 MWh per ton of H_2); the risk of technological dependence on imports (equipment for "green" metallurgy and electrolyzers are mostly produced abroad), it is necessary to take into account the real fact of incomplete use of the potential of ferrous metallurgy (modern blast furnace and converter technologies can already reduce emissions by 20–30% due to modern equipment for dust gas purification; partial replacement of coke with natural gas or hydrogen; transition to pulverized coal fuel with a smaller carbon footprint; optimization of the component composition and granulometry of the charge; stabilization of the properties of the agglomerate and pellets; recovery of thermal and chemical energy of gases, etc.).

In a state of war with Russian aggression, metallurgy in Ukraine in 2022-2023, according to [17], lost more than half of the metallurgical enterprises that were destroyed. Others significantly reduced production, lost their place in the world market and access to the export and domestic markets. The authors determine that in such conditions, metallurgical enterprises of Ukraine need to solve the problems of physical recovery, optimization of raw material and energy costs. The authors, relying on the fact that ~ 90% of steel is produced in the world using the technological scheme "blast furnace - oxygen converter", and the blast furnace produces a product, the use of which in the production of steel in the converter allows minimizing energy costs due to the rational use of the components of the potential of cast iron (its physical heat, and the carbon contained in cast iron), recognize that modern environmental requirements require a reduction in the "carbon footprint" in the production of metallurgical products, including by reducing the production of cast iron in blast furnaces.

The authors [18] propose to change the environmental situation and reduce CO_2 emissions from metallurgical production by expanding the use of direct iron reduction (DRI) technology using hydrogen and subsequent steel production in an electric arc furnace. Therefore, the relationship between business and state institutions should be built on the principles of partnership, mutual responsibility and strategic coordination. In their relationship, we are sure, the motto "your business - your problems" should not take place. Such a slogan has a more advertising or political connotation than a business one, which encourages interaction. In our opinion, the following factors can serve as the basis for their formation, the features of the impact and their main specific features should be analyzed separately.

Indirectness of business influence on scientific and technological progress. Thus, the metallurgical business does not create scientific and technological progress by itself, but only adapts the results of research, technological solutions and innovations that are formed in the scientific and educational environment and in state development programs. Accordingly, its profits are derived from the general level of development of science and technology.

To determine the external factors of influence that contribute to the development of the inventive abilities of an individual in the field of developing innovative metallurgical technologies, it is advisable to systematize them into several blocks according to the main features of their origin:

1. Scientific and educational environment:

- access to modern knowledge and research platforms (universities, scientific and research institutes, specialized laboratories);
- international academic mobility and exchange of experience;
- state and corporate support programs (scholarships, grants, incubators of ideas).

2. Production and technological environment:

- the presence of modern research and industrial sites for testing new technologies (pilot plants, experimental and industrial units);
- access to digital modeling (CFD, DEM, CAD/CAE) and industrial platforms for "smart manufacturing" (IIoT, big data in metallurgy) [19, 8], which allows, through the systematic use of CAD/CAE, to increase the effectiveness of training and the level of creativity of skills, reduce the time/cost of R&D and improve the quality of results;
- partnership with enterprises for the joint implementation of the results of inventive activity.

The use of industrial platforms (IIoT/Big Data): allows, according to [20], to provide predictive maintenance, stability of smelters, increase their energy efficiency and safety through inventive activity by pinching the cycle of "observation - abstract ideation - verification. In the context of innovation and problem solving, ideation - allows you to create new, non-standard ideas by breaking free from traditional thinking patterns. Successful ideation also involves not only generation, but also effective management, systematization and improvement of generated ideas to identify and implement the most valuable ones.

3. Socio-economic factors:

- state policy to support innovation (tax breaks, accelerated patenting procedure, venture financing);
- demand for innovation from the steel, alloys and non-ferrous metallurgy market (need for "green" technologies, energy-efficient, resource-saving and environmentally friendly processes);
- competitive economic environment that motivates to seek more effective solutions to maintain competitiveness.

4. Information and communication environment:

- open access to patent databases, international publications, scientific and technical literature;
- digital tools for collective development of ideas (online platforms, innovation clusters, hubs);
- developed communication channels between scientists, engineers and business (industry conferences, international exhibitions).

5. Cultural and psychological environment:

- public support and prestige of inventive activity;
- tolerance for risk and errors in the research process;
- formation of a culture of "open innovation" - a two-way mutual exchange of knowledge between different institutions and companies.

State institutions, we are sure, should perform the function of a key coordinator and investor in the field of fundamental and applied research. It should create a legislative framework, mechanisms for stimulating and protecting the interests of the national manufacturer.

Thus, the success of a scientist-inventor in the field of innovative metallurgy development depends not only on his own mental, emotional and professional potential (internal triad of "success" - Fig. 2), but also on external conditions - the availability of access to resources, a favorable innovation policy of the state, industrial-scientific partnership, as well as socio-cultural support for innovative activity, which make up the external pentad of factors of external origin.

In the study, for the first time, the triad of conditions as factors of internal origin and the influence of a complex of external conditions, including access to resources, a favorable innovation policy of the state, industrial-scientific partnership, as well as socio-cultural support for innovative activity, were substantiated and defined. Together they constitute a pentad of factors of external origin that ensure the development of innovative technologies of metallurgical production, determining the role and place of invention in it.

The authors of [21] consider the problems of the development of inventive activity in scientific institutions in Ukraine and the main barriers to this activity. The indicators of the development of inventive activity in scientific institutions of Ukraine, the issues of methodological support of inventive activity; management of this activity, the experience of organizing inventive activity in scientific institutions are studied. Proposals for improving and managing inventive activity at the level of state authorities and scientific institutions are substantiated.

Thus, the generalization of the factors of influence and the definition of the conditions for the development of inventiveness, consistent with the capabilities of the components of the potential of the individual (mental, emotional and professional) allowed us to highlight the following sources as the main ones, contributing to their rational implementation by substantiating effective innovative solutions.

The need for a partnership model. Relations between business and state institutions should be based on:

- agreed goals: development of strategic industries, industrial modernization, reduction of energy consumption, greening of production;
- on a system of mutual obligations: business invests in production modernization and efficiency improvement, the state invests in scientific

developments, personnel training, infrastructure;

- on social responsibility: taking into account the interests of society (ecology, employment, regional development).

Thus, the profits of the metallurgical business directly depend on the use of the results of scientific and technological progress, therefore relations with state institutions should be based on partnership, joint responsibility and coordination of the interests of science, business and society. And the development of scientific knowledge about the physicochemical essence of processes, as objects of research, with the aim of their improvement is a continuous, objective in terms of sources of origin and logical in terms of the consequences of implementation, process. The main requirement for the practical implementation of the acquired scientific and practical knowledge in the form of a formed life cycle of a process/production method or one of its stages is their compliance with the main features of the invention, with the achievement of significant positive effects, which become sources of increasing levels of energy efficiency, resource conservation, environmental friendliness, productivity, product quality, etc., indicators important for the competitiveness of the process.

The superficial level of knowledge about the physicochemical essence of modern processes of production of cast iron and steel, other materials, which form the corresponding potential of useful properties of raw materials, fuel and energy resources, does not allow to achieve rational in terms of costs and effective in terms of results of their implementation. Physicochemical properties of the initial potential of external factors are an obligatory part of the process, the parameters of which play the role of activator of physicochemical transformations in a given direction, their dynamic development with completion when obtaining the expected result. Of particular importance for the inventor is also practical experience, which is formed during experiments with conducting research on high-temperature models in conditions close to real metallurgical processes.

When improving existing technological schemes for the production of ferrous metals and alloys, it is necessary to realize that between the levels of optimal, i.e. theoretically possible level of perfection, and the actual, which is formed from modern technological solutions, there is a certain gap - a vacuum. Its use is possible provided that the researcher has the components of the individual's potential, which, determining the IQ level, allow applying its components to reduce the gap between theory and practice. This is possible only if there is knowledge about the physicochemical nature of the processes that are the object of improvement, as well as practical skills for their application in existing production conditions.

Conclusions.

The choice of the optimal technology depends on economic, technical and environmental factors, as well as on the scale of production and the availability of resources. An important role in the restoration of the economy of Ukraine by improving metallurgical processes is played by the use of innovative technological solutions, the source of which is invention. The implementation of solutions that meet modern requirements for energy efficiency, resource conservation and environmental safety will allow overcoming the technical lag and bringing the industry to the forefront.

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Розробка методу лазерного зміцнення поверхні ковзання залізничних коліс

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Development of a method for laser strengthening of railway wheel tread

Анотація. *Метою роботи була розробка методу лазерного зміцнення зони викружки залізничних коліс для отримання бейнітної структури і усунення підрізу гребенів.* ***Методика.*** *Лазерне опромінення зразків проводили в режимі безперервного випромінювання на пристрої ЛГ-701 «Кардамон» (потужність випромінювання 600 Вт, швидкість переміщення лазерного променю – 20, 15, 10 і 5 мм/с). Вимірювали твердість і мікротвердість зразків. Випробування на зношування зразків колісної сталі після різних режимів лазерного опромінення проводили на випробувальній машині «СМЦ-2» (метод кочення з проковзуванням). Дослідження проводили за допомогою оптичного мікроскопу «Neophot-31», а також шляхом рентгеноструктурного аналізу.* ***Результати.*** *За аналізом літературних джерел доказано доцільність локального зміцнення зони викружки поверхні ковзання залізничних коліс шляхом лазерної обробки. На основі дослідження зношеного колеса показано, що протікання інтенсивних пластичних зсувів в умовах дії високих контактних напружень під час експлуатації призводить до інтенсивного зношування в зоні викружки, що може призвести до підрізу гребенів.* ***Наукова новизна.*** *Показано, що після лазерної обробки в режимі безперервного випромінювання можна отримати мікрокомпозитну бейнітну структуру лазерно-зміцненого шару, яка сприятлива для умов експлуатації. При цьому параметри зміцненого шару, тонкої структури сталі, а також мікротвердість і твердість можна варіювати у певних межах залежно від вихідного стану колісної сталі, а також режиму безперервного лазерного впливу. На основі порівняльного аналізу показано, що режими лазерної обробки, а також ступінь дисперсності вихідної мікроструктури визначають ефект лазерного зміцнення колісної сталі. Запропоновано перспективний режим з потужністю лазерного променю 600 Вт і швидкістю його переміщення 5–15 мм/с, який рекомендовано використовувати у поєднанні з традиційною термічною обробкою.* ***Практична значущість.*** *Обговорено перспективи локальної лазерної обробки викружки з отриманням мікрокомпозитної бейнітної структури в режимі безперервного лазерного випромінювання, що дозволить не тільки підвищити зносостійкість поверхні ковзання залізничних коліс, а й знизить ризик підрізу гребенів у процесі експлуатації. Такій обробці можна піддавати як нові залізничні колеса після традиційної термічної обробки, так і використовувати її в залізничних депо під час проведення відновлення зношених профілів поверхні ковзання шляхом переточок.*
Ключові слова: *залізничне колесо, колісна сталь, поверхня ковзання, бейніт, мікрокомпозитна структура, лазерна обробка, зміцнення, зносостійкість.*

Abstract. Purpose. *The goal of this work was to develop a method for laser strengthening of the cove zone of railway wheels in order to obtain a bainitic structure and eliminate undercutting of the crests.* ***Methodology***. *Laser irradiation of the samples was performed in continuous radiation mode using the LG-701 “Cardamon” device (radiation power: 600 W; laser beam movement speeds: 20, 15, 10, and 5 mm/s). The hardness and microhardness of the samples were measured. Wear tests of the wheel steel samples, after different laser irradiation modes, were conducted on the “SMC-2” testing machine using the rolling with slipping method. The research was carried out using a Neophot-31 optical microscope, as well as X-ray structural analysis.* ***Findings.*** *According to the analysis of literary sources, the feasibility of locally strengthening the cove zone of the tread through laser treatment has been demonstrated. Based on a study of railway wheels worn during operation, which exhibit different tread profiles, it has been shown that intense plastic shear flow under high contact stress conditions leads to accelerated wear in the cove zone. This wear can result in the undercutting of the wheel flanges.* ***Originality.*** *It has been shown that during laser processing in continuous radiation mode, it is possible to obtain a microcomposite bainitic structure in the laser-strengthened layer, which is favorable under operating conditions. At the same time, the characteristics of the strengthened layer – such as the fine steel structure, microhardness, and hardness – can be varied within certain limits depending on the initial state of the wheel steel and the parameters of the continuous laser exposure. A comparative analysis demonstrates that both the laser processing parameters and the degree of dispersion in the initial microstructure significantly influence the effect of laser strengthening on wheel steel. A promising processing mode, involving a laser beam power of 600 W and a speed of its movement of 5–15 mm/s, is proposed and is recommended for use, particularly in combination with traditional heat treatment.* ***Practical value.*** *The prospects of local laser processing of the wheel tread to obtain a microcomposite bainitic structure using continuous laser radiation are discussed. This approach not only increases the wear resistance of railway wheel treads but also reduces the risk of crest undercutting during operation. This treatment can be applied both to new railway wheels after traditional heat treatment and during the restoration of worn tread profiles by regrinding in railway depots.*
Key words: *railway wheel, wheel steel, tread, bainite, microcomposite structure, laser processing, strengthening, wear resistance.*

Вступ. Під час експлуатації залізничне колесо знаходиться в складному напруженому стані, який визначається системою контактних, динамічних і циклічних напружень [1]. Всі ці напруження викликають в колесі пружно-пластичні та теплові явища, сприяють втомним процесам у ободі й диску, підрізу гребеня та руйнуванню поверхні ковзання [2–7], де виникають різного роду ушкодження: зношування поверхні ковзання (зміна профілю поверхні ободу за колом ковзання), підріз гребенів, дефекти теплового впливу (повзуни, навари, гальмівні вищербини, термічні тріщини), втомне викришування, крихкі тріщини. В останні роки суттєво зріс інтерес до вивчення механізму зношування поверхні ковзання, що обумовлено не тільки необхідністю скорочення пов'язаних зі зношування втрат, але також із розробкою ефективних методів підвищення довговічності коліс, забезпеченням надійності їх роботи, особливо в екстремальних умовах (великі навантаження, високі швидкості, вплив підвищених температур на затяжних спусках тощо) [2–6].

Слід зазначити, що були спроби локального зміцнення гребенів коліс з метою боротьби з бічним зношуванням за допомогою плазмового впливу [8] та нагрівання струмом високої частоти [9]. Термічне зміцнення поверхні ковзання залізничних коліс за допомогою лазерної обробки також є одним з перспективних напрямів сучасного наукового пошуку [10–12]. Однією з найважливіших переваг лазерної обробки металовиробів є її висока гнучкість завдяки можливості нагрівання обмежених ділянок поверхні за дуже короткі проміжки часу [13–15]. Слід зазначити, що були запропоновані методи зміцнення поверхні ковзання та гребенів за допомогою волоконного лазеру [16], у результаті чого формувались дисперсні мартенситні структури у зоні лазерного впливу, які сприяють крихкості ободів і тому є неприпустимими в колісній сталі. Перспективною слід вважати локальну лазерну обробку зони викружки з метою отримання бейнітної структури колісної сталі, яка за своїми властивостями є сприятливою для умов експлуатації залізничних коліс [7, 17]. Цей метод пов'язаний з використанням безперервної лазерної дії, оскільки за умов імпульсної лазерної обробки структура загартованого шару виявляється ідентичною «білим шарам», що утворюються на поверхні ковзання під час експлуатації [7, 17]. Окремо слід відзначити додаткову позитивну дію лазерної обробки, яка сприяє фрагментації неметалевих включень в лазерно-зміцненому шарі, що діють як концентратори напружень [18], а також суттєвому гальмуванню корозійних процесів і утворення тріщин поблизу неметалевих включень при подальшому навантаженні за час експлуатації. Це пов'язано із взаємодією включень і сталевої матриці, яка призводить до утворення мікрокомпозитних зон і зміні когезівної міцності міжфазних границь включення-матриця [19–22]. Мета роботи – розробка методу лазерного зміцнення зони викружки залізничних коліс для отримання бейнітної структури і усунення підрізу гребенів.

Матеріали і методи досліджень. Досліджено зношене колесо № 1, а також колеса № 2 і 3 виробництва ПАТ «ІНТЕРПАЙП НТЗ», що зазнали термічну обробку ободу (гартування від 860 °С, відпуск за температури 520 °С з витримуванням 2 год.), а також диску після гарячої деформації в інтервалі температур 1250–850 °С (охолодженого на повітрі від температури 850 °С). Хімічний склад сталей досліджуваних коліс наведено у табл. 1.

Таблиця 1. Хімічний склад сталей досліджуваних коліс

№ колеса	Вміст елементів, % ваг.								
	C	Mn	Si	S	P	Cr	Ni	Cu	Al	Ti
1	0,59	0,72	0,34	0,025	0,012	0,14	0,15	0,20	–	–
2	0,58	0,74	0,34	0,025	0,011	0,14	0,17	0,21	–	–
3	0,58	0,76	0,35	0,030	0,009	0,04	0,05	0,11	0,04	0,05

Дослідження проводили за допомогою оптичного мікроскопу «Neophot-31», а також шляхом рентгеноструктурного аналізу. Лазерне опромінення сталі проводили у режимі безперервного випромінювання на пристрої ЛГ-701 «Кардамон» (потужність випромінювання 600 Вт, швидкість переміщення лазерного променю – 20, 15, 10 і 5 мм/с, рис. 1, а). Вимірювали твердість і мікротвердість зразків. Випробування на зношування зразків колісної сталі після різних режимів лазерного опромінення проводили на випробувальній машині «СМЦ-2» (метод кочення з проковзуванням). Попередньо було виготовлено контртіла, що імітують рейку, частина з яких також піддавалась лазерній обробці за відповідним режимом. Зразки зважували до і після випробувань для визначення втрати ваги у результаті зношування.

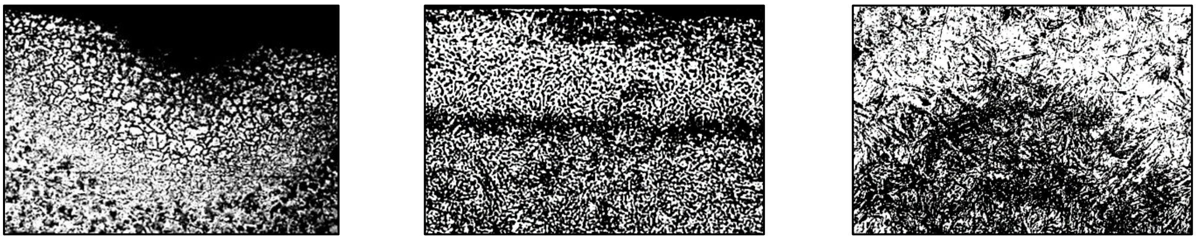
Результати досліджень та їх обговорення. При візуальному огляді зношеного колеса виявлені такі дефекти, як повзун, відшарування, наплив металу з поверхні ковзання на зовнішню бічну грань ободу, втомно-корозійне зношування. У результаті напливу відбулося спотворення профілю колеса в процесі експлуатації (рис. 1, б). У зоні викружки спостерігається ділянка локалізованої деформації, а також мікротріщини (рис. 1, в).

а б в

Рис. 1. Сліди від безперервної лазерної дії на поверхні зразків колісної сталі (а) та ділянка зношеної поверхні ковзання (б, в): а – ×10, в – ×100

Мікроструктура ободів коліс № 2 і 3 після гартування представляла собою перліт і ферит, після відпуску – відпущений тонкодисперсний перліт (троостит) і ферит. Після гарячої деформації та нормалізації диску отримали перлітно-феритну структуру сталі, яка відрізняється від структури термічно обробленої сталі більшими розмірами зерен перліту і фериту та меншим ступенем дисперсності перліту.

Мікроструктура зони лазерної обробки сталі, яка була попередньо загартована і відпущена у промислових умовах, являє собою дисперсний мартенсит або бейніт, залишковий аустеніт і дисперсний цементит (рис. 2). Характер основної структури сталі, визначеної за допомогою рентгеноструктурного аналізу, залежить від швидкості переміщення лазерного променю: за швидкості 20 мм/с, коли інтенсивність охолодження сталі максимальна, отримали мартенсит (за результатом перетворення аустеніт → мартенсит), за інших режимів лазерної обробки – бейніт (за результатом перетворення аустеніт → бейніт). Оскільки мартенситна структура на поверхні ковзання є неприпустимою, представляється перспективною бейнітна структура лазерного гартування.



а б в

Рис. 2. Мікроструктура колісних сталей після лазерної і попередньої термічної обробок: а – колесо № 2; б, в – колесо № 3; а – ×200; б, в – ×500

У табл. 2 наведено результати впливу режиму лазерної обробки безперервної дії на параметри тонкої структури колісної сталі. У разі попередньої термічної обробки параметри мікровикривлень у решітці, величини блоків і щільності дислокацій свідчать про більшу міру зміцнення сталі під час лазерної обробки у порівнянні з вихідним гарячедеформованим і нормалізованим станом, що визначається впливом напружень у вихідній структурі колісної сталі.

Аналіз впливу режиму лазерної обробки, а саме швидкості переміщення лазерного променю, показав, що зі зменшенням часу високоенергетичного впливу знижується рівень зміцнення колісної сталі. Закономірності зміни параметрів тонкої структури сталі після лазерної обробки полягають у тому, що зі збільшенням швидкості переміщення променю блоки мозаїки стають дрібнішими, а мікровикривлення в решітці зростають, зростає і щільність дислокацій. Це пов'язано з розвитком часткової релаксації напружень за умови зменшення швидкості переміщення лазерного променю.

Аналіз особливостей зони лазерного впливу показав, що її мікроструктура складається з (рис. 3):

- саме ділянки з бейнітною структурою (1), що має ширину S_1;
- перехідної зони з бейнітно-перлітною структурою (2), яка має ширину S_2;
- зони термічного впливу (3), яка має ширину S_3 в залежності від режиму опромінення (рис. 2, б, в).

У табл. 3 наведено розміри означених структурних зон. Таким чином, у результаті лазерного опромінення отримана мікрокомпозитна (градієнтна) структура зони лазерної обробки. При цьому перехідна зона (2) забезпечує міцне зчеплення шару з бейнітною структурою із основною структурою колісної сталі (зоною термічного впливу), що підвищує стійкість до крихкого руйнування. Загальна ширина зони лазерного впливу від одного проходу лазерного променю (S) складається:

$$S = S_1 + 2S_2 + 2S_3. \quad (1)$$

Глибина зміцненого шару h складала 1,2–1,6 мм в залежності від режиму опромінення:

$$h = S_1 + S_2 + S_3, \quad (2)$$

причому значення S_2 та S_3 практично є однаковими у напрямках ширини та глибини дії лазерного променю.

Таблиця 2. Параметри тонкої структури зони лазерного зміцнення колісної сталі після обробки безперервною лазерною дією

Вихідний стан сталі	Швидкість руху лазерного променю, мм/с	Розмір блоків, $\cdot10^5$, см	Мікровикривлення $\Delta a/a$	Щільність дислокацій, $\rho^{\perp}$, см$^{-2}$
Гаряче-деформований	Початковий відлік	3,52	Початковий відлік	$2{,}3\cdot10^8$
	5	0,72	0,35	$4{,}2\cdot10^{11}$
	10	1,22	0,35	$3{,}48\cdot10^{11}$
	15	1,71	0,32	$2{,}1\cdot10^{10}$
	20	1,82	0,30	$1{,}7\cdot10^{10}$
Після термічної обробки	Початковий відлік	3,31	Початковий відлік	$4{,}7\cdot10^{10}$
	5	0,48	0,38	$6{,}3\cdot10^{11}$
	10	0,54	0,37	$3{,}6\cdot10^{11}$
	15	0,62	0,36	$2{,}4\cdot10^{11}$
	20	0,69	0,36	$2{,}3\cdot10^{11}$

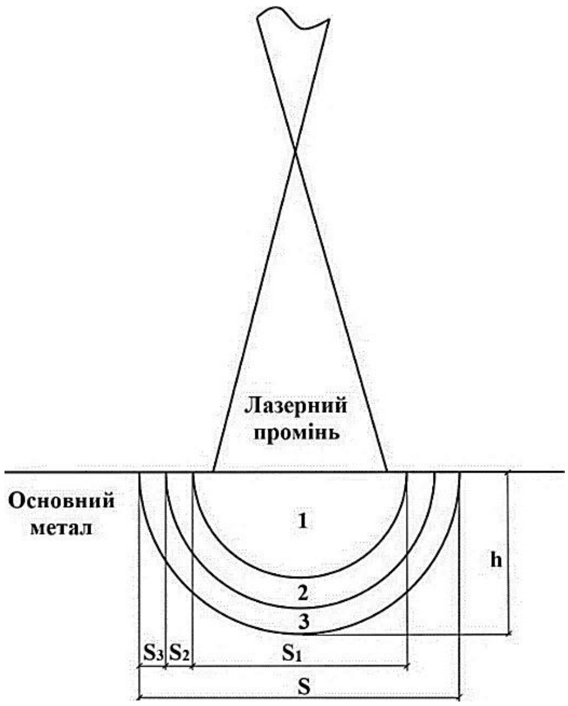


Рис. 3. Схема структури зони лазерного зміцнення

Таблиця 3. Ширина градієнтних ділянок зони лазерного впливу

Ширина структурної зони, мм		
S_1	S_2	S_3
1,3–1,9	$(30–70)\cdot10^{-3}$	0,3–0,8

Мікрокомпозитна зона лазерного впливу, що виникла у результаті бейнітного перетворення аустеніту з різною швидкістю внаслідок неоднорідного розподілу температури за шириною і глибиною дії лазерного опромінення, забезпечує перепади значень мікротвердості сталі у зоні опромінення (табл. 4). Зона лазерного впливу має композитну структуру за ознаками змінних фазового складу та мікротвердості.

Мікротвердість і твердість зміцненого лазерною обробкою шару зі збільшенням швидкості руху лазерного променю зростають, що пов'язано зі збільшенням внутрішніх напружень і щільності дефектів кристалічної будови (табл. 5). Зона термічного впливу після лазерної обробки мікроструктурно виражена слабо. Зі збільшенням швидкості руху променю, тобто зі зменшенням часу лазерного впливу, глибина зміцненої зони зменшується. За всіх швидкостей переміщення лазерного променю мікротвердість попередньо термічно обробленої сталі є вищою у порівнянні з нормалізованим станом після гарячої деформації (табл. 5).

Таблиця 4. Показники мікротвердості ділянок зони лазерного впливу (швидкість руху лазерного променю $V_{пр}$ = 15 мм/с)

Ділянка у зоні лазерного впливу	Мікротвердість, МПа
1	5680
2	3850
3	3300

Таблиця 5. Зміна мікротвердості колісної сталі від поверхні у глибину зразка після лазерної обробки

$V_{пр}$, мм/с	Вихідний стан сталі	Відстань від поверхні зразка, мкм							
		0	100	200	300	400	500	600	700
5	Після термообробки	4400/4580	4300/4470	4200/4320	3900/4070	3000/3200	3000/3180	2900/3080	2900/3070
15	Після термообробки	5500/5680	5300/5510	4400/4560	3100/3280	3100/3240	3000/3180	2900/3040	2900/3030
5	Гаряче-деформований	3800/3960	3800/3950	3500/3680	3100/3290	2400/2610	2300/2490	2300/2480	2300/2480
15	Гаряче-деформований	4600/4790	4400/4570	3400/3620	2500/2740	2400/2660	2300/2470	2300/2460	2300/2460
Примітка: значення у чисельнику та знаменнику – колесо № 2 і колесо № 3 відповідно.									

Таким чином, при безперервному лазерному випромінюванні поверхневий шар колісної сталі зміцнюється у результаті значного диспергування структури, збільшення щільності дефектів кристалічної будови, дроблення блоків мозаїки та зростання мікровикривлень у кристалічній решітці, а також утворення мікрокомпозитної структури за результатом бейнітного перетворення. Зміна швидкості руху лазерного променю дозволяє варіювати рівень зміцнення сталі та глибину зміцненої зони, а також характер структури сталі. Оскільки наявність мартенситної структури на поверхні ковзання є неприпустимою, представляється перспективною бейнітна структура лазерного гартування.

Режими лазерної обробки визначають ефект лазерного зміцнення колісної сталі. Перспективним слід вважати режим з потужністю лазерного променю 600 Вт і швидкістю його переміщення 5–15 мм/с, особливо у поєднанні з традиційною термічною обробкою залізничних коліс. Оскільки у цьому дослідженні були отримані значення мікротвердості лазерно-зміцненого шару колісної сталі, підданої попередній термічній обробці, вищі за 360 НВ і не ставилося завдання отримання рекордних значень цього показника, представляється можливим рекомендувати загальноприйняті заводські режими попередньої традиційної термічної обробки ободів залізничних коліс (температури гартування 840–860 °С і відпуску 480–550 °С відповідно для коліс різних розмірів і сталей різного хімічного складу). Слід зазначити, що під час локального лазерного зміцнення зони викружки в умовах виробництва залізничних коліс доцільним є проведення цієї операції після гартування перед відпуском. У такому разі відпуск призведе до зменшення термічних напружень.

Для дослідження зносостійкості колісної сталі після лазерної обробки проводили випробування на зношування. Результати випробувань наведено у табл. 6. Аналіз результатів випробувань показав ефективність лазерної обробки колісної сталі у режимі безперервного впливу з отриманням бейнітної структури лазерно-зміцненого шару. Особливо це проявилося у разі поєднання звичайної термічної і лазерної обробок. Зносостійкість зразків колісної сталі підвищилася у середньому на 70 %, зносостійкість контртіла також підвищилася на 10 % у разі рейкової сталі без лазерної обробки і на 62 % у разі рейкової сталі після лазерної обробки. Очевидно, що лазерна обробка в режимі безперервного впливу призводить до суттєвого підвищення зносостійкості колісної сталі (зниженню інтенсивності зношування), особливо якщо цій обробці піддається пара тертя або один з елементів пари тертя. Це свідчить про перспективність спільної обробки коліс і рейок, у першу чергу в локальних проблемних ділянках. Зокрема, у залізничного колеса – це зона викружки.

Підвищення зносостійкості колісної сталі після лазерної обробки підтверджує ефективність застосування зміцнювальної лазерної технології за рахунок цілеспрямованого використання внутрішніх резервів структурної пристосованості поверхневих шарів сталі в умовах експлуатації. Вивчення структури тонкого поверхневого шару після випробувань на зношування показало пластичну поведінку лазерно-зміцненої структури без утворення тріщин.

Очевидно, що для отримання мінімального коефіцієнту тертя для пари колесо-рейка необхідно, щоб у лазерно-загартованій структурі сталі під час експлуатації реалізовувалися пластичні перетворення, що призводить до збільшення щільності дислокацій на робочій поверхні та пластичної релаксації напружень. Це зумовлює доцільність додаткового локального лазерного зміцнення робочої поверхні залізничних рейок.

Таблиця 6. Результати випробувань на зношування зразків колісної сталі після лазерної обробки

Пара тертя	Початкова вага зразка, г	Вага зразка після випробувань, г	Втрата ваги, г	Відношення зносостійкості зміцненого і вихідного матеріалу
Колісна сталь, т/о, без ЛО – рейкова сталь без ЛО	86,87 / 85,03	85,60 / 83,83	1,27 / 1,20	1,0 / 1,0
Колісна сталь, г/д, ЛО, $V_{пр}$ = 15 мм/с – рейкова сталь без ЛО	81,86 / 84,11	80,94 / 83,32	0,92 / 0,79	1,38 / 1,51
Колісна сталь, г/д, ЛО, $V_{пр}$ = 15 мм/с – рейкова сталь після ЛО	81,46 / 86,33	80,61 / 85,59	0,85 / 0,74	1,49 / 1,62
Колісна сталь, т/о, ЛО, $V_{пр}$ = 15 мм/с – рейкова сталь без ЛО	82,03 / 84,02	81,22 / 83,31	0,81 / 0,71	1,56 / 1,69
Колісна сталь, т/о, ЛО, $V_{пр}$ = 15 мм/с – рейкова сталь після ЛО	82,22 / 80,21	81,44 / 79,52	0,78 / 0,69	1,62 / 1,74

Примітка: ЛО – лазерна обробка; г/д – гаряча деформація; т/о – термічна обробка; $V_{пр}$ – швидкість переміщення лазерного променю. Значення у чисельнику та знаменнику – колесо № 2 і колесо № 3 відповідно.

Висновки

1. Дослідження зношених у процесі експлуатації залізничних коліс показало, що протікання інтенсивних пластичних зсувів в умовах дії досить високих контактних напружень призводить до інтенсивного зношування в зоні викружки, що може призвести до підрізу гребенів. При цьому доцільним є локальне зміцнення зони викружки з метою вирішення зазначених проблем.

2. Під час лазерної обробки в режимі безперервного випромінювання утворюється мікрокомпозитна бейнітна структура лазерно-зміцненого шару, яка сприятлива для умов експлуатації. Параметри зміцненого шару, тонкої структури сталі, а також твердість можна варіювати у певних діапазонах залежно від вихідного стану колісної сталі, а також режиму безперервного лазерного впливу.

3. Режими лазерної обробки, а також ступінь дисперсності вихідної мікроструктури визначають ефект лазерного зміцнення колісної сталі. Перспективним є режим з потужністю лазерного променю 600 Вт і швидкістю його переміщення 5–15 мм/с, особливо у поєднанні з традиційною термічною обробкою.

4. Підвищення зносостійкості колісної сталі після лазерної обробки показує ефективність застосування зміцнювальної лазерної технології шляхом цілеспрямованого використання внутрішніх резервів структурної пристосованості поверхневих шарів сталі в умовах експлуатації. Представляється перспективною локальна лазерна обробка викружки, що дозволить не тільки підвищити зносостійкість поверхні ковзання залізничних коліс, а й знизить ризик підрізу гребенів у процесі експлуатації. Такій обробці можна піддавати як нові залізничні колеса після традиційної термічної обробки, так і використовувати її у залізничних депо під час проведення відновлення зношених профілів поверхні ковзання шляхом переточок.

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Мішалкін А. П., Петренко В. О., Селегей А. М., Фонарьова Т. А.

Раціональні шляхи формування, використання та відновлення виробничого потенціалу металургійного підприємства

Mishalkin A.P., Petrenko V.O., Selegei A.M., Fonarova T.A.

Rational ways of forming, utilization and restoration of the production potential of a metallurgical enterprise

Анотація. *Мета та завдання. Теоретико-аналітичне обґрунтування категорії «виробничий потенціал підприємства»; визначення, на основі аналізу існуючих наукових поглядів, його основних специфічних складових та умов раціональної реалізації його складових у металургійному виробництві; визначення факторів зовнішнього впливу, які визначають динаміку раціонального використання складових потенціалу та ефективні способи формування виробничого потенціалу підприємства. Методика. Комплексний системний метод наукового обґрунтування умов забезпечення позитивного балансу між складовими виробничого потенціалу підприємства та раціонального використання його ресурсно-сировинної складової на основних етапах життєвого шляху виробничого процесу. Наукова новизна. Уточнено сутність «потенціалу» як категорії, що визначає здатність об'єкта або його складових під впливом певних факторів зовнішньої дії трансформувати комплекс вихідних властивостей, сформованих природним або штучним способом, в комплекс споживчих властивостей продукції, які забезпечують мінливі за вимогами потреби суспільства. Практична значимість. З урахуванням стану вітчизняного ГМК та потреб суспільства в забезпеченні його соціально-економічного розвитку запропоновано комплексну схему, запровадження якої дозволить найбільш раціонально використати корисні властивості наявних потенціалів металургійного виробництва.*

Abstract. *Purpose and objectives. To provide a theoretical and analytical substantiation of the category "production potential of an enterprise"; to identify, based on the analysis of existing scientific approaches, its main specific components and the conditions for their rational implementation in metallurgical production; to determine external factors influencing the dynamics of the rational use of potential components and effective methods for forming the production potential of an enterprise.Methodology. A comprehensive systematic approach to scientifically substantiate the conditions for ensuring a positive balance between the components of an enterprise's production potential and the rational use of its resource and raw material component at the main stages of the production process life cycle. Scientific novelty. The concept of "potential" is clarified as a category that defines the ability of an object or its components, under the influence of certain external factors, to transform a set of initial properties (formed naturally or artificially) into a set of consumer properties of products that meet the evolving needs of society. Practical significance. Taking into account the current state of the domestic mining and metallurgical complex and the societal demand for socio-economic development, a comprehensive framework is proposed. Its implementation will enable the most rational use of the beneficial properties of the existing potentials of metallurgical production.*

Introduction. "Potential" as a term has become widespread among scientists to determine rational ways of using available or still hidden material resources, equipment involved in the production process and the capabilities of an enterprise. Their potentials, as components of the total, are realized in the course of a business entity's activities.

Assessment of the overall potential of the enterprise's production strength makes it possible to identify areas for further improvement of existing technologies and to find ways to effectively use its useful components. In addition to the cost-benefit assessment of the technical and economic indicators of the production process, it is important to determine the rational degree of use of the useful properties of the components of the enterprise's initial potential.

Natural resources can be divided into groups according to their "exhaustion": conditionally inexhaustible (energy of the sun, wind, water, atom, etc.); exhaustible non-renewable (mineral raw materials, fossil fuels, etc.) and renewable (materials of plant origin and waste from their industrial processing). It is advisable to distinguish a separate group of man-made waste, which is inevitable at this level of development of science and technology. The latter group, through special treatment, becomes a reserve of raw materials in the context of depletion of the potential of raw materials.

The task important for solving the current problems of ferrous metallurgy is the scientific substantiation of conditions that will ensure a positive balance between the components of the production potential of the enterprise and the rational use of its resource and raw material component at all major stages of the life of the production process, which are implemented according to the scheme shown in Fig. 1.

Based on the lifecycle analysis of physicochemical potential of the metallurgical system under study, the factors whose impact on the system will increase the level of utilization of its physical and chemical potential will be determined.

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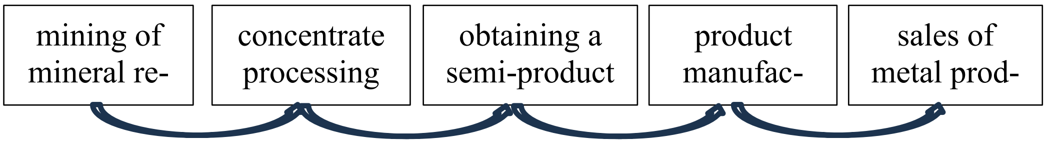

Figure 1 – Main stages of the production process lifecycle

Based on the lifecycle analysis of physicochemical potential of the metallurgical system under study, the factors whose impact on the system will increase the level of utilization of its physical and chemical potential will be determined.

In a generalized form, “production potential” should be defined as sources, means or opportunities that can be used to solve problems to achieve a certain goal in a certain area by creating appropriate conditions for the realization of useful components of the potential. In essence, this category defines the capabilities of the relevant object to use its properties in modern production processes, which have been hidden until a certain time.

The metallurgical industry is a complex of enterprises engaged in multifunctional activities that must be stable in development and resistant to negative risks and threats of both external and internal origin. The balanced use of the properties of the components of the initial production potential of enterprises in this industry ensures its stable development. Interaction of external factors and properties of the potential is a condition for the effective implementation of the life cycle of the production process in terms of final results. The properties of potentials of artificially created methods of external influence are used in almost all known spheres of activity created by using the intellectual component of human personal potential.

During the evolutionary development of society with the corresponding development of the individual's intellect, in accordance with the requirements of society, the quantitative, qualitative composition and ratio of useful properties of the potentials determined for use changed. The capabilities of this component of the individual's potential are used to improve technology and equipment, develop resource-saving, energy-efficient and rational production methods for mineral raw materials and energy resources. This potential also allowed us to develop our own clone, artificial intelligence.

Analytical review of recent studies and publications. The paper examines specific varieties of the category “potential” by identifying their components, sources of origin, conditions of formation, and directions for the rational use of their elements. Data on the depletion of mineral resources indicate that the currently known reserves of mineral raw materials will be exhausted within the coming decades [1]. According to the *Mining Encyclopedia* [2], which is based on research from 2001, deposits of aluminum ores will be depleted in the next 55 years, chromium – in 154 years, coal – in 150, iron – in 173, oil – in 50, and natural gas – in 49 years.
Despite the discovery of new deposits of mineral resources, the time when reserves of metal ores and fuel-energy resources will be exhausted is approaching. The recently developed “theory of natural resource depletion” is interpreted as the “onset of natural hunger.”

According to forecasts, the reserves of natural resources will last for only 3 to 6 generations. Therefore, solving this problem is vital for humanity. The period of resource use on our planet can be extended by reducing their consumption, developing methods for their rational use, and involving alternative and renewable energy sources, as well as the useful potential of technogenic waste, in production processes.
Thus, in addition to the growing imbalance between societal development and natural resources outlined in [1], it is also reasonable to add the irrational use of the potential of mineral and energy resources in modern production processes as a cause of the current situation.

Since the invention of production methods based on human labor activity, all means created by humans, as well as the possibilities of their implementation and improvement, have come to be referred to as "potentials."

Subsequently, these were classified according to their specific properties, source of origin, usage directions, and impact on the environment.

According to our interpretation — which has the right to exist — in order to evaluate the quantity and quality of the capacities of natural and artificial resources, researchers have borrowed the long-established concept of “potential” from physics, mathematics, chemistry, and other exact sciences.

All material elements around us that have been created by nature can be regarded as components of the Earth's initial potential. Humans use them in their activities.
The strength of the general potential and the rational use of its natural and artificial components ensure a country’s economic independence and sovereignty.

The analysis of research results concerning the essence of the concept of “potential” revealed a tendency toward constant changes in its interpretation [3]. Significant discrepancies were found both in defining the essence of the category “potential” and in identifying its components.

Nineteen approaches to managing the competitive potential of an enterprise were identified, which are reasonably considered its components. The author of study [4], analyzing the evolution of economic thought regarding the enterprise potential from 1981 to 2018, states that during this period, fourteen types of enterprise potential have been distinguished in domestic literature.

The systematization of approaches to defining the essence of the category "potential" enabled the author to identify three main types of potential: resource-based, goal-oriented, and systemic.

In study [5], an attempt was made to classify potentials according to their specific features.

For instance, the authors of [6] classified potential using thirty criteria and identified as many as seventy-four of its types. According to the authors, this makes it possible to reflect various aspects of potential in enterprise management. Reflect – perhaps. But doubts arise regarding their practical application. The author of study [7] believes that the elements of an enterprise's production potential are resources in any way related to the functioning and development of the enterprise. Choosing the most important ones from such a large number is a complex issue.

The author further defines enterprise potential as a complex system, which makes it impossible to study without identifying its components and the links between them. Once again, defining potential solely as an economic category, the researchers overlook the fact that its origin lies in the exact sciences: mathematics, physics, and chemistry. It must be acknowledged that the essence of the main properties of potentials, as well as the corresponding processes, is physico-chemical in nature.

Thus, the attempts presented in scientific literature to classify the components of potentials based on their specific characteristics are not perfect. The dynamic increase in the number of identified potentials and their components does not contribute to a deeper understanding of the essence of these categories. Many questions regarding the components of the metallurgical enterprise's potential remain debatable. An important direction for further scientific research is to determine the role and influence of production potential in the formation of the enterprise's overall potential in interaction with other types.

We believe that reaching a consensus amid the large number of different perspectives on the components of production potential is possible by identifying individual components whose interaction forms the basis of the production process.

The author of [7] concluded that it is impossible to produce highly profitable products and generate profit without the full and rational use of an enterprise's production potential and the organization of uninterrupted operations. Rational and full use of the initial production potential is a rather complex task, and "full" does not always mean "rational". At certain stages of the production process, the notion of "full" utilization may even contradict the intended goal. Therefore, the answer to the question of the most optimal ratio of these characteristics can be found through an investigation of the specifics of using the physico-chemical potential of production processes, with a focus on determining a sufficient level of its utilization to achieve the set objective.

Figure 2 presents a diagram of the formation and rational use of the components of production potential at the main stages of metallurgical production, which takes into account:

the specific features of the metallurgical enterprise's activity,

the interconnections between its structural elements,

influence of external factors on the formation of its components,

the correlations between the initial properties of production process components and the qualities and properties of the final product.

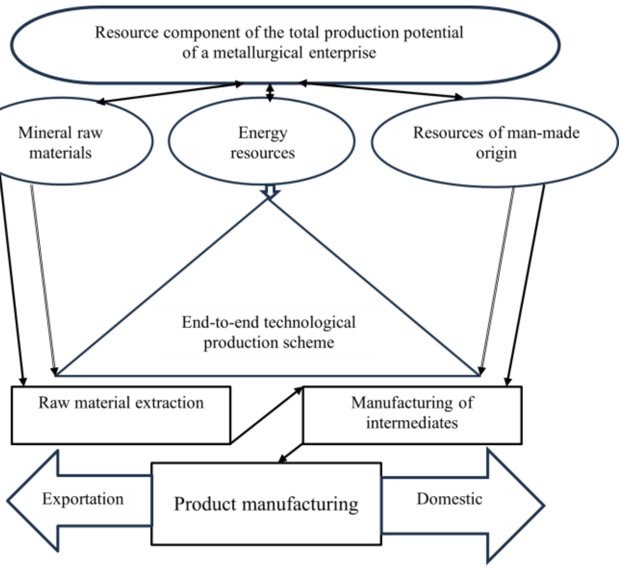

Fig. 2 – Diagram of the Formation and Rational Use of the Components of Production Potential at the Key Stages of Metallurgical Production

The review of scientific sources conducted in this study led to the conclusion that the most widely used interpretation of the term “enterprise potential” is as a combination of natural conditions and resources, opportunities, and reserves that can be utilized to achieve the set goals. As important components of its production potential, it is advisable to define the potentials of raw materials, energy, technology, and equipment. These components, in interaction, determine the characteristics of the production process, and the category of “enterprise production potential”, in our opinion, is more universal in terms of the essence and importance of its components.
It is also necessary to highlight the importance of other potentials as measures for creating conditions for the rational, safe use of the enterprise’s production potential: organizational-management, financial-economic, psychological-emotional, compliance, and other components.

The most common method in modern economic methodology for assessing the enterprise's potential is its cost and expense assessment [8]. In the study of strategic management of the economic potential of a metallurgical enterprise [9], the principles of potential evaluation were substantiated; the characteristic features of the enterprise's potential as an economic system were provided; the factors were analyzed, and the technology of anti-crisis management of the enterprise's potential was defined.

Discussion of Results.

Nature, long before the appearance of humans, created a resource, or more precisely, a raw material-energy potential in the form of deposits of mineral raw materials, coal, gas, oil, and others. Humans, in their activities, utilize the beneficial properties of the components of this potential, which have a physicochemical basis.

In the course of its operations, an enterprise forms its overall potential from the following components, which determine the scope of their functional purpose and realize their potential in technological processes: production, innovation, financial, market, intellectual, organizational, informational, investment, security, and others.

The use of the formed initial production potential of the enterprise should be viewed as creating conditions for transforming the potential properties of the initial object – the metallurgical system – into the real qualities of the newly created object. It is important to note that most studies on determining the characteristics of the enterprise's potential analyze the significant organizational, managerial, security, and economic factors involved in its formation and utilization. However, the crucial issues concerning the use of the initial physicochemical potentials (FCP) of the components of the real metallurgical system remain almost ignored by scientists.

The dynamics of utilizing the components of potential are determined by the specific features and technological needs of the production processes. Continuous and rational use of the beneficial properties of the components of the production potential is one of the conditions for ensuring the stability of the processes that produce high-quality, competitive products. As a result of the use of certain properties, the initial potential requires determining effective sources and methods for its restoration, ensuring its reserves.

The stability of the enterprise's activities and its production processes is a factor influencing the final production results, determining both its qualitative indicators and the rationality of the components of the enterprise's potential that were used. Stability is ensured if the potential real resources of raw materials and energy meet the level of current resource needs, sufficient for producing products in the planned period.

Thus, the basis for the majority of processes, both of natural origin and those artificially created by humans, such as the production of metals and alloys, is the use of the physicochemical potential of the resources involved in them. The level of its utilization depends on the effectiveness of external actions on the physicochemical potential of the metallurgical system, which consists of mineral raw materials, energy, and other materials. The externally controlled action, which has its corresponding potential properties (oxidizing, reducing, thermal, etc.), takes the potential of the initial physicochemical properties out of dynamic equilibrium, initiating the development and realization of transformations at the relevant stages of the technological process.

The methods of forming and implementing the physicochemical potential of metallurgical systems (FCPMS) have been realized in modern technologies for the production of ferrous metals and alloys. Further improvement of existing technologies is based on achieving a rational interaction between the resource and raw material component of the production potential and the potential of external influences on the metallurgical system in terms of costs for raw materials and energy.

Conclusions.

Resource potential, as one of the main components of the enterprise’s production potential, which is formed from resources of natural origin and artificially created, is defined as the synthesized physicochemical potential of their initial properties within a material object. The latter, under the influence of external factors, can transform its initial physicochemical properties into a product with the expected quality and characteristics.

The category of “potential” requires not further popularization, but rather an expansion of the spectrum of its components, as yet unused possibilities, which should be determined based on scientific justification of its appropriateness and practical significance for the development of human activities. Greater attention from scientists is required to address the problem of increasing the utilization of the resource and raw material components of the production potential of a metallurgical enterprise by justifying, developing, and applying effective methods of external influence on the metallurgical system being studied.

It has been established that the development of the concept of restoring the level of development of domestic metallurgical production, which will have significant chances of implementation, is possible through the mandatory fulfillment of the following conditions: reorganization of relationships in the "market – enterprise – state" system; achieving a balance between the pace of development of economic and social processes as required by society; changes in the market conditions of the domestic and international markets for iron ore, energy resources, and metal products, which will ensure the long-term stability of the raw material base of the metallurgical industry and the sustainable development of enterprises in the industry.

In conditions of uncertainty, counteracting the risks that arise when internal regulations, conditions, and rules are violated (the fulfillment of which is mandatory) is the potential of functional properties of the compliance control service, the use of which promotes the targeted, safe, and high-quality use of the components of the enterprise's production potential.

Priority tasks also include creating conditions for enterprises, with substantial support from the state, that will allow for the effective implementation of investment and innovation measures.

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CONTENT

ЗМІСТ

ТЕОРІЯ І ПРАКТИКА МЕТАЛУРГІЇ
науково-виробничий журнал

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