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Stages of technological improvement of the process of continuous casting of iron-carbon and copper billets

***Abstract.** In the article there are presented the stages of improvement of the process of continuous casting. It is revealed, that at the each stage of technological improvement of the process of continuous casting, the damage parameters of billets were reduced. Improvement of the process of continuous casting leads to the improvement of the mechanical properties of the billets and the performance of continuous casting machines. The first stage is shown as the process of transition of the number of experimental developments into quality, during which the casting of billets passed from an unstable process to a stable one. The second stage is characterized by the creation of new improved continuous casting processes. So, besides the existing machines of the vertical type, radial, curvilinear and horizontal casting machines were invented. By the end of the twentieth century, this technological process reached the limit of the possibilities for increasing the quality of performs, and the productivity of continuous casting machines. It is shown that the third stage is intended for continuous casting of copper alloys and is based on the influence of the frequency of the movement of the billets and the reverse movement of the perform during overcoming the static friction force. It was determined that for the frequency of*



movement of billets made of copper alloys, which are in the range of 2.5 ... 7.5 min⁻¹, the direction of its movement during overcoming the static friction affects the mechanical properties of the billet. The fourth stage - causes an increase in the mechanical properties of the billet due to the use of inertia forces in the alternating movement of the billet. It was revealed that at the fourth stage the mechanical properties of the billets increased most effectively, and the linear performance increased from 0.4 ... 0.8 to 2.5 ... 4.0 m/min, and in some cases to 5.0 ... 7.0 m/min.

Keywords: *continuous casting of billets; reverse and forward motion; copper alloys; damage parameter*

Introduction.

Currently, the process of continuous casting is gaining immense popularity. For example, in 1990, when analyzing the usability of this process, it was shown that in all industrialized countries, from 88 to 95% of all the smelted metal and alloys were cast on continuous casting machines. Over the past 20 years, the linear productivity of continuous casting of steel billets has increased from 0.8...1.0 to 4.0...6.0 m/min. Today many scientific researchers of continuous casting are concern with the ways of improvement of the mechanical properties of the billets, which lead to high linear productivity of continuous casting machines without reducing the quality of the billets. These and other similar questions determined the relevance of this study and prompted to analyze the entire history of improving the continuous casting process from the point of view of the development of technological capabilities of the continuous casting process, which arose in parallel with the development of the science of damage to materials, namely the theory of continual damage.

We propose to divide the entire path of development of the continuous casting process from its origin to the present day into four stages.

1. The first stage - the transformation of the number of experimental developments that combine the design of machines and technological processes of continuous casting during the transition from an unstable process of production of billets into a stable process.

2. The second stage: expansion of opportunities for the continuous casting process within the created interval of the rheological state of the billet, due to the current cyclogram of the operation of the continuous casting machine and reaching the limit of possibilities for increasing the quality of the billets and the productivity of continuous casting machines.

3. The third stage is an insignificant increase in productivity of a horizontal continuous casting machine (HCCM), an increase in the mechanical properties of billets from copper (and non-ferrous) alloys and a change in the rheological state of the billets due to a change in the direction of movement of the billet during overcoming the friction and static force frequency of movement from 2.5 to 7.5 min⁻¹.

4. The fourth stage causes a change in the rheological state of the billet and an increase in the mechanical properties of the billets by reducing the parameter of its

damageability, which depends on a significant increase in the frequency of movement of the billet to 120...150 min⁻¹ and the use of inertial forces during alternating movement of the billet aimed at mechanical effects in the emerging billet.

Thus, the main task of our work is to confirm the coincidence of the next reduction in the damage of the billet and the declared next improvement of the continuous casting process, as well as to show the connection of the reduction in the damage of the billet with some changes in the control of the speed of the billet and the direction of movement of the billet in the cycle.

Experimental and theoretical methods.

For the first time, the technology of producing billets was created and patented in 1826. In the work (Schwarzmeier, 1962, p. 62) it is indicated that the patent under No. 3023 under the name “Lead pipes” was obtained by J. Lying in the United States of America in 1826. The process of continuous casting efficiently differs from the process of casting into molds in that the billet is continuously moving along the stationary water-cooled wall. As a matter of fact, an analog of the conveyor production of billets was developed, which according to calculations made it possible to significantly increase the productivity of the created machine and increase the yield of casting from 65...70% to 90...94%.

At the end of the 19th century, the growing demand for industrial billets required manufacturers to create a new technological process for producing billets with higher productivity of the manufacturing process and a higher density of billets and usable casting yield. The disadvantage of the process with non-stop motion of the billet was that fatigue processes were not studied in the billets located in the crystallization temperature range, which led to the appearance of micro cracks and their rapid development. As a result, a billet was obtained, which cannot be further processed or a breakage” of the billet was obtained in the plane perpendicular to the axis of the billet, which caused the termination of the casting process. During the time from the first patent to the continuous casting method to the present day, the continuous casting process has evolved from an unstable process to a stable, automated continuous casting process.

Periodically, industrial enterprises impose demands on producers of billets to increase the productivity of continuous casting machines and improve the quality of billets. Apparently, these requirements were once again voiced in the 30s, the results were obtained in the middle of the 50s. This can be confirmed by the quotation by V. Schwarzmayer, who in 1957 in the preface to the German edition of the book «Continuous Casting» wrote the following: « ... in the last 25 years, several methods have been practically applied, further improved by certain companies» (Schwarzmayer, 1962, p. 68).

The horizontal continuous casting machine built by the Ukrainian Research Institute of Metals for the Leninskaya Kuznitsa plant in the 1980s looked like this, Fig.1. At that time, the “movement – pause” cyclogram was laid in the HCCM, as in

all continuous casting machines of the former USSR. This machine worked from 1984 to 1991.

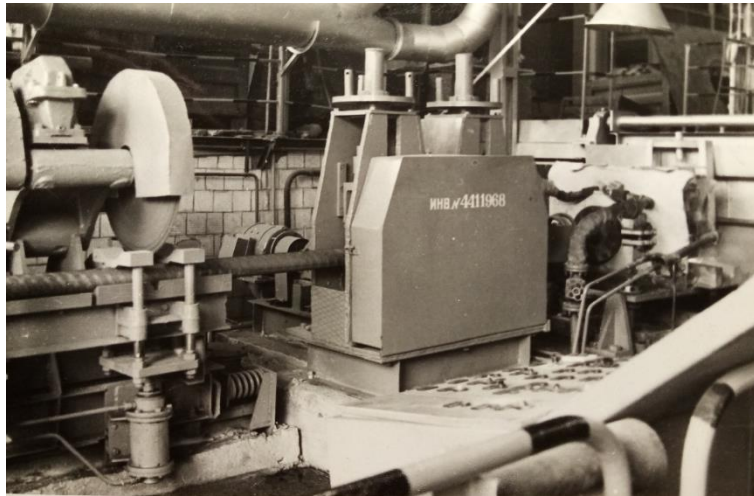


Figure 1. Horizontal continuous casting machine for copper alloy billets (Author's photo).

The main method for determining the damage parameter of copper alloys billet of the BrT5Z5L5, BrO10P, and BrA19I3C made on a horizontal continuous casting machine at the frequency of the billet movement in the range of $2.5...7.5 \text{ min}^{-1}$ and at different directions of movement of the billet during overcoming the force of static friction. Most often, to determine the damage parameter of continuously casted billets, the following operations were performed:

- production of billets for copper alloys samples of the BrT5Z5L5, BrO10P and BrA19I3C with various technological parameters of the continuous casting process according to the following scheme on an experimental machine for horizontal continuous casting (Fig. 2).



Figure 2. Experimental machine of horizontal continuous casting of copper alloy billets «Energoprom» LLC (Author's photo).

At this horizontal continuous casting machine, bronze billets of BrT5Z5L5 with a diameter of 0.5 m were obtained at various frequencies of the movement of the billet. It was necessary to conduct statistical studies to determine creep. 30 samples were made for each frequency of the movement of the billet listed in the Table 1.

Table 1. Planning the modes of movement of billets for making samples for testing.

Name of copper alloys	Billets movement frequency, f , min^{-1}	The direction of movement of the billets while overcoming the static friction force	Number of billets for samples, pcs
BrO5Z5C5	2,5	Reverse	30
	5,0		30
	7,5		30
	2,5	Progressive	30
	5,0		30
	7,5		30

- tensile test according to GOST All-Union State Standard 1497-84 (Metals, 1984);
- creep test according to GOST All-Union State Standard 3248-81 (Metals, 1981).

For a better understanding of the processes occurring in the sample during testing, in table 2 we give the chemical composition of bronzes of various grades, from which the test samples were made. For convenience, in this table, each chemical element is designated by generally accepted chemical symbols.

Table 2. The chemical composition of the applied bronzes.

Bronze grade	The chemical composition of the main components, (wt%)						
	Sn	Al	Zn	Pb	Fe	P	Cu
BrO5Z5C5	4.0–6.0	–	4.0–6.0	4.0–6.0	–	–	additives
BrO10P	9.0–11.0	–	–	–	–	0.4–1.1	additives
BrA9I3C	–	8.0–10.5	–	–	2.0–4.0	–	additives

Thus, as it was shown by experiments of testing samples on an AIMA 5-2 machine, as the temperature increases (T_L) from (0.3...0.5) T_L to (0.9...0.95) T_L , the creep rate of the viscous portion of the billets, which is located in the mold, increased tens of thousands of times. Given these conditions, for the implementation of these tests, a new way to test samples at temperatures (0.9...0.95) T_L and improved standard equipment were developed and patented (Fig. 3), (Khoroshylov, Ponomarenko, & Shatahin, 2006a; Horoshilov & Ponomarenko, 2007).

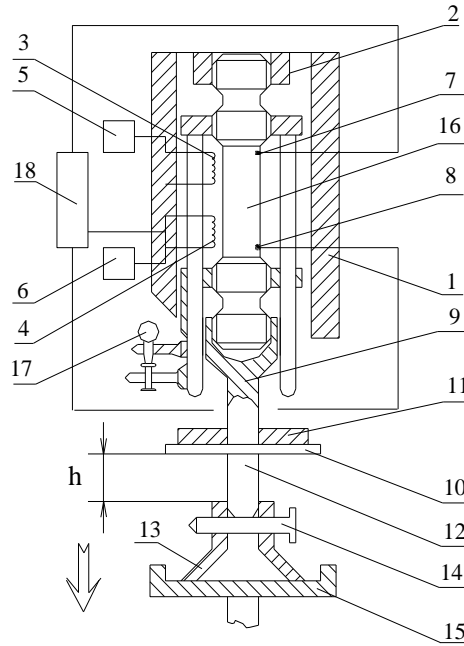


Figure 3. Scheme of an improved machine for testing specimens of copper alloys in the temperature range $(0.9-0.95) T_L$ (Horoshilov & Ponomarenko, 2007):
 1 – cylindrical heat-shielding casing; 2 – top link; 3,4 – upper and lower electric heaters, respectively; 5,6 – temperature regulators for the upper and lower electric heaters, respectively; 7, 8 – upper and lower thermocouples, respectively; 9 – thrust of direct loading; 10 – cargo; 11 – vertical rod; 12 – support; 13 – horizontal bar; 14 – plate of thermal stress compensator; 15 – sample for testing; 16 – deformation indicator 17 – block for comparison of temperatures from thermocouples.

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	7,5		30
	2,5	Progressive	30
	5,0		30
	7,5		30

Statistical processing of the results of measurements of creep indices in the crystallization temperature range (Horoshilov, Mel'nichenko, & Segal, 2017):

– to determine the damage parameter of samples from the indicated grades of copper alloys that are in the crystallization temperature range (0.9...0.95) T_L , we use the Bailey-Norton and Rabotnov-Kachanov formula (Bailey et al., 1968; Kachanov, 1958; Orowan, 1952; Rabotnov, 1959):

– there is a special technique for determining the coefficients for equations (1) and (2), described in (Breslavskij et al., 2007; 2008), and according to which experiments should be carried out according to the data presented in Table 4.

Table. 4. Timing of destruction of samples at two boundary temperatures T_1 and T_2 and two boundary pressures σ_1 and σ_2 .

№	Temperature T, °C	Pressure σ, MPA	Time t, s
1	T_1	σ_1	Specific experimental values
2	T_1	σ_2	Specific experimental values
3	T_2	σ_1	Specific experimental values
4	T_2	σ_2	Specific experimental values

Since in the crystallization temperature range, creep is the main mechanism of deformation and fracture, then from the data presented in Table. 2 (at the time of destruction time known from experiments) there is a method for determining the coefficients n , k , β_0 , which is described in (Breslavskij et al., 2008):

– processing the results of experimental studies to determine the creep of the samples before their destruction obtained at various technological parameters of the continuous casting process were obtained by the following method described in (Horoshilov, Mel'nichenko, & Segal, 2017);

– based on experimental studies to determine the degree of increase in the mechanical properties of the billet as by increasing the duration of the pause (with the cyclic movement of the billet), and due to a complex action: increase the frequency of movement of the billet and the direction of movement of the billet during overcoming the static friction force (Khoroshylov, 2013, p. 22).

Results and its discussion.

The main condition by which we will determine the emergence of a new stage in the improvement of continuous casting is a slight decrease in the damage parameter of the billets. Reducing the damage parameter allows you to change the rheological state of the billet, which allows you to improve the mechanical properties of the billet, and this in turn allows you to improve the performance of the continuous casting machine.

Due to the fact that in the process of continuous casting there are two opposite actions, that is why the following rule can be applied to this casting process: changes in the mechanical properties of the billets (by reducing the damage parameter) follow

the change in the sequence of technological operations. This rule is valid for any stage of technological improvement of the continuous casting process.

The first stage is the stage of unstable operation of continuous casting machines, turning the number of experimental studies from the first quarter of the nineteenth to the sixties of the twentieth century into an increase in the stability of the continuous casting process, the quality of the billets and an increase in the productivity of continuous casting machines. Despite the fact that the first patent for the design of the machine and the implementation of the continuous casting process was obtained in the first quarter of the nineteenth century, however, a more meaningful improvement to the process already created was started only in the end of XIX till the beginning of XX.

The most active in those years was the work on mastering the process of continuous casting in Germany. The first patent in Germany, according to (Schwarzmeir, 1962, p. 9), was a mold for casting wire, which in 1883 was received by E. Levanser (1882) from Paris. Thus, from 1883 to 1913, 36 patents were registered in Germany, with many applicants from such countries as Britain, the United States, and France. It could only mean that in the four countries there was a powerful industrial complex, which allowed itself to build patented continuous casting machines. At that time, the theoretical and practical issues of reducing the rate of fatigue in metals and alloys did not find wide applications in industry. The time for the emergence of progressive methods for casting billets came only when it was necessary to organize the production of billets on an industrial scale from alloys, to which higher demands were placed on their mechanical properties.

In 1914, a patent (Person, 1913) for a method and device for the vertical semicontinuous casting of tubular billets with the help of a crystallizer that billets reciprocating movements. This method was simultaneously patented in Germany, Britain, the USA and Austria. Vertical continuous casting with a "swing" of the mold formed a separate direction, which was constantly improved and began to appear in other countries (Person, 1913). It should also be noted that, until 1963, vertical-type continuous casting machines were used on an industrial scale, in which the billet was formed and cut on a vertical section.

It must be said that the significance of this technical solution Person "mold swing" will be disclosed later. In order to preserve the "swinging of the mold" in the vertical plane, the designs of the continuous casting machines will be changed. However, it is necessary to take into account the technological necessity, in which the vertical axis of the workpiece should be maintained at the inlet of the melt to the mold, and at the exit of the workpiece from the machine, it should have a horizontal axis.

In the same period, a patent was obtained for a method for the production of billets from metals prone to cracking, which was claimed in 1944, and obtained in 1953 (Schorndorf, 1944). In the same period, two more technical solutions registered in German patents were developed. So in 1939, H. Ruppik (Germany) filed a patent (Ruppik, 1939) for the method of continuous casting of steel billets, and in 1953,

P. P. Brenner received a patent (Brenner, 1942) for a method of casting billets of unlimited length.

From this it follows that at the first stage of technological improvement of the continuous casting process by the middle of the 50s, technical solutions were obtained that allowed reducing the damage parameter of the billet – these are patents (Brenner, 1942; Person, 1913; Schorndorf, 1944), on the basis of these technical solutions it is also possible to cast steel billets. There is also a British patent and a US Patent for a continuous casting plant (Mellen, 1915) with a priority date of 1915 and 1916, but after this message, there was no tangible development of events on the issue of continuous casting of steel due to the unsatisfactory stability of the continuous casting process. As the author (Shatagin, Sladkoshteev, & Vartazarov, 1974, p. 88) points out, with non-stop movement of the billet from copper alloys during continuous casting “even at very low casting speeds of the order of 0.05...0.13 m/min, the process was stopped at the very beginning due to the breakage of the billet (Fig. 4). On the basis of 60 experimental castings, it was established that the stability of the casting process is ensured when the billet moves with periodic stops. In the middle of the 60s of the XX century, the authors of work (Shatagin, Sladkoshteev, & Vartazarov, 1974, p. 76) developed the process of continuous casting of copper alloy billets for horizontal machines.



Figure 4. Billet, which was taken from the non-stop movement (Shatagin, Sladkoshteev, & Vartazarov, 1974, p. 76)

The second stage began in the period from the mid-60s to the 90s of the twentieth century. The active development of the developed technologies takes place. A brief classification of methods for the production of billets is presented in Fig. 5.

In the late 50s, articles were written on the issue of creep, damage, and long-term strength. In the 60s...70s the books of Y. N. Rabotnova, L. M. Kachanova and I. I. Malinin appeared (Katshanov, 1974; Malinin, 1975; Rabotnov, 1966). After that, the theory turned into a practical plane. Standardization of Bailey-Norton and Rabotnov-Kachanov on the determination of damage parameters for structural materials, systems at a temperature from 0.3 to 0.5 liquidus temperature (T_L) of the alloys under study.

In the 1980s, an idea emerged about determining the damage parameter of a viscous section of a solidifying billet in order to control the damageability of the billet using the technological parameters of the continuous casting process. To estimate the

value of the damage parameter at all stages of technological improvement of the continuous casting process, a unique method was used at all stages to determine the rheological state of the billet based on the Bailey-Norton and Rabotnov-Kachanov equations to estimate the damage parameter of continuously cast billets (Bailey et al., 1968; Kachanov, 1958; Orowan, 1952; Rabotnov, 1959).

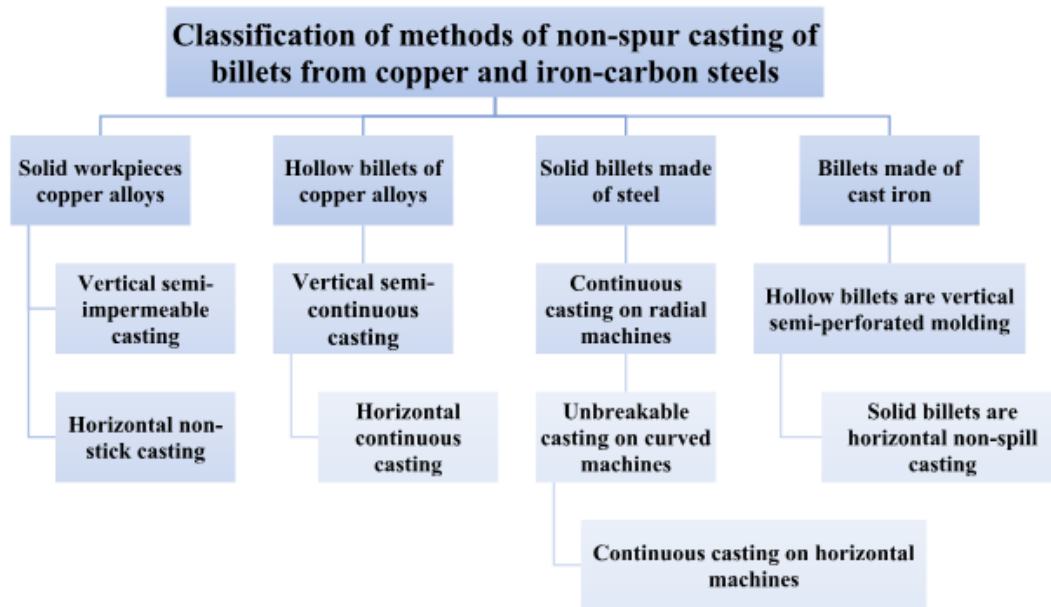


Figure 5. Classification of methods of non-spur casting of billets from copper and iron-carbon steels

Before determining the parameter of damage to the billet, depending on the continuous casting conditions, it is necessary to determine the forces acting on the billet on the experimental machine, and then on the testing machine at the temperature corresponding to the crystallization temperature interval, determine the creep rate with the corresponding force acting on the billet. After that, according to the method described in (Breslavskij et al., 2008), the damage parameter was determined.

For the calculation of stress fields, deformations, displacements, and a parameter of damage, software programs designed to solve creep problems under a two-dimensional stress state are usually used. The analysis of the obtained results shows that the processes of damage accumulation slow down with the further solidification of the local part of the billet (Breslavskij et al., 2007).

Analyzing (Shatagin, Sladkoshteev, & Vartazarov, 1974, p. 88) the basic technological parameters of horizontal continuous casting of 140 experienced castings of solid and hollow bronze billets, the authors indicate that «...with the periodic pulling of solid billets, it was possible to immediately increase the casting time to 13 hours and 12 minutes». For hollow billets, casting time increased from 12 minutes to 10 hours and 45 minutes.

In addition to the technical re-equipment of the metallurgical complex and an intensive experimental search in the developed countries of the World, in 1952, 1958, and 1959 the works of such scientists in the field of damage zone (destruction of metal structures) were published. Such scientists as E. Orowan, L. M. Kachanova and Y. N. Rabotnova, and in 1968, there were published the works of the following authors: P. B. Bailey. These works will further be the basis for creating formulas for determining the parameter of damageability of metal structures. One of the varieties of these formulas:

$$\varepsilon = \beta_0 \cdot \sigma^n \cdot \exp(k_1 \cdot T) t, \quad (1)$$

$$\sigma_* = \frac{K \exp(k_2 \cdot T)}{t_*} \quad (2)$$

where ε is a creep test sample, %; σ is a stress in the sample, MPa; σ_* is a long-term strength, which is the stress in the cross-section of the billet, leading it to destruction over time t_* . T – test temperature, °C; t is the current time, sec.; K, β_0, n, k_1, k_2 are empirical coefficients.

Based on experimental data, empirical coefficients were obtained (Breslavskij et al., 2007; 2008). For this purpose, experimental studies have been carried out in the temperature range of crystallization to determine the dependencies of damage (creep) as a function of temperature and time. As a result of these data, a methodology was developed for determining empirical coefficients. It is shown in the works (Breslavskij et al., 2008) and (Khoroshylov, 2013, p. 21), a change in the sequence of technological operations in the process of continuous casting, which led to a decrease in the parameter of damageability of the billet. The reasons preceding the change in the sequence of technological operations were that, after a pause, the beginning of the movement in the subsequent cycle was associated with overcoming the force of static friction. The tensile force acting on the billet during the overcoming of the friction force of rest (FFR), 2 times greater than the effort to overcome the force of sliding friction. This suggests that during the overcoming of the FFR, the rate of damage to the billet increases significantly. So, during the overcoming of the FFR, microcracks are likely to form, which develops during the overcoming of the sliding friction force, forming already visible cracks.

This results of experimental studies presented in the work (Khoroshylov, 2013, p. 22), in which the phenomenon of reducing the parameter of damage to the billet when using reverse movement while overcoming the static friction force with the frequency of its movement in the mold $2.5 \dots 7.5 \text{ min}^{-1}$, is identified.

At the same time, it was not previously taken into account that, after a pause during the start of the movement, the billet must overcome the force of static friction. As it was shown in the work (Khoroshylov, 2013, p. 23; Khoroshylov, Podolyak,

Kuryliak, Kipensky, & Lomakin, 2020) in which, during the overcoming of the friction force of rest in the cross-section of the billet, there are forces that are 1.42–2.0 times greater than the force of sliding friction. It is known that during the cyclic movement of the billet inside the mold, a force is applied to the billet, which is able to overcome the force of static friction. Therefore, the reason for the occurrence of microcracks lies precisely at the moment of overcoming the friction force of rest under the condition of the translational movement of the billet. After the formation of a microcrack during overcoming the force of sliding friction, the microcrack develops and turns into a crack.

In the work (Breslavskij et al., 2007), it was decided that in order to avoid the appearance of microcracks while overcoming the static friction force, it was decided to make a reverse movement. During the reverse movement, the overcoming of the friction force at rest occurs during the compression of the billet, this significantly reduces the possibility of microcracking. It was tested both on the experimental and industrial continuous casting machines at LLC «Energoprom», Kharkiv. During the tests of technological parameters of the continuous casting process, according to the researchers, the indicators of the speed and step size of the reverse movement of the billet were rational to use and were patented (Horoshilov et al., 2008; Khoroshylov, Ponomarenko, & Shatahin, 2006a; 2006b). However, the quality of the charge currently in circulation does not allow to obtain billets with acceptable mechanical properties that could be obtained earlier.

Refusal of non-stop movement of continuously cast billets became possible after obtaining a patent (Person, 1913), in which the technological process of vertical semi-continuous casting (intermittent casting) was developed using the reciprocating vertical mold and the design of a semi-continuous casting machine.

As the author of (Khoroshylov, 2013, p. 1) points out, the Ukrainian Scientific Research Institute of Metals (USRIM) V. Sladkoshteev, O. Shatagin played a major role in creating horizontal continuous casting machines for billets of iron-carbon and non-ferrous alloys. However, the first specialists in the USSR to create horizontal machines were the brothers A. N. Myasoedov and A. N. Myasoyedov (Myasoyedov, 1939), although their research is little known. Indeed, there are copyright certificates relating to this period of work USRIM (Sladkoshteev, Shatagin, & Krupennik, 1965; Sladkoshteev et al., 1967; Sladkoshteev, Shatagin, & Vartazarov 1968a; 1968b; Sladkoshteev et al., 1968) in which the sequence of inventive work of the institute is displayed.

A distinctive feature of the continuous casting of non-ferrous alloys is that the billet is in contact with the intermediate graphite bushing, in contrast to the fact that steel billets should be cast only in copper crystallizers. A graphite sleeve paired with a hardened billet of copper alloys has a friction coefficient (FC) of about 0.1, and a pair of copper (crystallizer) – low carbon steel (billet) FC – 0.36.

In the 1960s, in spite of the fact that the origins of the theory of continual damage appeared, the need to pause during continuous casting was heuristically justified, probably by V. T. Sladkoshteev and O. A. Shatagin. The sequence diagram with a

pause duration allowed the horizontal positioning of the mold, both for casting non-ferrous and for iron-carbon alloys. In those years, it was problematic to create a horizontal “swinging” mold due to the sliding joint of the metal receiver and the mold.

In addition, in the same years, machines with various technological processes for the production of pipes were also built for the casting of cast iron billets of standard length. So in 1964, work appeared on mastering the production of pipes on centrifugal casting machines, and four years later, in Belarus, a plant was built for continuous casting of cast iron pipes using the method of vertical semi-continuous casting with a “swinging” mold (Ivanov & Baranov, 1968, p. 176; Baranov, 1968, p. 124). The advantage of these processes is that the yield of continuous casting is 10...12% higher than that of centrifugal.

The desire to reduce the height of the vertical continuous casting machine has led to the creation of installations of radial and curvilinear types. On the radial caster, the mold and the secondary cooling device guides are located on an arc of a certain radius. At the end of the radial section, the billet passes through the correcting and pulling rollers and is brought to the horizontal position, in which cutting to measured lengths is performed. On a curvature-type caster, the mold and a part of the secondary cooling zone have a constant radius, then the radius increases, and the billet gradually straightens.

HCCM of radial and curvilinear types, in which the incompletely hardened billet goes to the horizontal section. This allows you to significantly increase the speed of continuous casting with large sections of the billets, since the cutting site can be located at a sufficiently large distance from the mold (30-35 m). The total height of such installations, as a rule, does not exceed 12 m (Kovrjakov, 2004, p.13; Nikiforov, Vdovin, & Piksayev, 2004; Yamaguchi, Sawai, & Nakashima, 2013, p. 7).

With the horizontal arrangement of the mold, it was decided to abandon its forward-return motion. In the cyclogram of the movement of the billet it was significantly increased the duration of the pause. From the data presented in the work (Berner & Kronmyuller, 1969, p. 89) on the basis of pilot industrial studies, the duration of the pause afterward began to exceed the duration of the translational movement of the billet in 3...4 times.

Refusal from the non-stop movement of continuously cast billets could theoretically be possible after the publication of papers: (Bailey et al., 1968; Kachanov, 1958; Orowan, 1952; Rabotnov, 1959) in which the mechanisms of crack development are considered and mathematically described and are estimated long-term strength using a sample with a crack perpendicular to the direction of stretching. Indicators that affect the damage to the billet are presented in this work. The most common type of damaged billet is a crack, it is caused by the creep of the test specimen, equation (1). In turn, creep is influenced by the stress in the cross section of the sample (fig. 2 item 16), temperature, which affects the strength properties of the test specimen and the time the voltage is applied to the sample. Equation (2) is the long-term strength of the material of the billet or sample, which in turn is represented by specific stress in the

cross-section of the billet. This voltage should lead to the complete destruction of the sample or billet over time (Breslavskij et al., 2008).

Ten years later, monographs on the subject of continuous casting of steel billets and billets of copper alloys were published (Shatagin, Sladkoshteev, & Vartazarov, 1974, p. 7; Shatagin & Sladkoshteev, 1976, p. 5), which identified the advantages and disadvantages of operating continuous casting machines.

The first stage of improving the continuous casting process (ICCP) implies two cases of changing the sequence of technological operations. In the first case, this is a change in the non-stop movement of the billet on a forward-return ("swing" of the mold) and the second case is a change in the non-stop movement of the billet on a cyclical movement, with time out for pause. In these two cases, the researchers gradually reduced the damage parameter of the continuously cast billet to a certain value corresponding to the level of technological development.

«Swinging» (alternating movement) of the mold is a translational-return movement of it, in which, despite the non-stop movement of the billet, the speed of movement of the mold relative to the billet has a variable value at which the minimum speed of their relative movement is zero. It should be noted that on a vertical continuous casting machine, the billet moves at a constant speed, and the mold makes up and down cyclical movements. When moving up the mold creates tensile stress in the billet, contributing to the appearance of deformations and microcracks in the frame of the billet, and when moving down the mold creates compressive stresses in the billet that contribute to the closure of microcracks. The "swinging" of the mold introduced into the first stage of the ICCP an increase in the frequency of the billet movement relative to the mold up to about 30...60 min⁻¹ (once a minute), as well as the possibility of stopping the billet, due to which the movement of the billet appeared to be cyclical and decrease its destruction rate in comparison with the non-stop movement).

In addition, as indicated above, the translational movement of the mold due to the compression force can completely or partially close the microcracks that appear, which in turn improves the mechanical properties of the billets (Person, 1913). Therefore, in the same time period, a patent was obtained for a method for the production of billets from metals prone to cracking, which was claimed in 1944 and obtained in 1953 (Schorndorf, 1944).

As follows from the literature, in the period from the mid-10s to the 50s...60s of the twentieth century, the following stages of the first stage of the technological ICCP were carried out, which made it possible to reduce the damageability:

1. It became possible to carry out the reciprocating-progressive movement of the mold relative to the billet (Person, 1913);

2. Getting a method for producing a billet of unlimited length means the appearance of several things:

- 2.1. Firstly, billets of unlimited length from non-ferrous alloys can be obtained only on machines of the horizontal type;

– for horizontal casting, the cyclogram of operation of a horizontal continuous casting machine did not apply the “swinging” of the mold, and the movement of the billet was carried out according to the scheme: “movement – pause”;

– the appearance of a pause in the cyclogram made it possible to regulate the mechanical properties of the billets (the methods for regulating which are discussed below);

2.2. Secondly, for the continuous casting of steel billets, the design of a radial continuous casting machine was created. The design assumes to combine the positive qualities of the "swinging" mold and bring the technological axis of the billet (or slab) into a horizontal plane, which will allow obtaining billets of unlimited length.

The second and third stages of improving the continuous casting process are based on the development of patents (Person, 1913; Ruppik, 1940). Patent (Person, 1913) has allowed ensuring an acceptable quality of the billets and the speed of continuous casting on vertical continuous casting machines when the mold is “swung”. At present, vertical semicontinuous casting machines are still preserved for casting their cast iron hollow billets. However, there are drawbacks of a constructive solution with a vertical technological axis of the billet:

– this design limits the length of the cast billet.

– creates a danger in the delivery of molten metal to a height of more than 20...30 m;

The second patent (Ruppik, 1939) provided for obtaining billets of unlimited length. At the moment, there are two options for obtaining billets of unlimited length.

Benefits:

1. In the technological plan, instead of the non-stop movement of the billets, it was carried out:

– in the case of vertical continuous casting, the non-stop movement of the billet is replaced by alternating cyclic movement (“swing” of the mold);

– for the created horizontal process of continuous casting with the cyclic movement of the billet according to the “movement-pause” scheme, time was paused, and the duration of the pause was 3...4 times longer than the duration of the translational movement of the billet.

2. Changing the design of the continuous casting machine. After 1963, a horizontal continuous casting machine for casting non-ferrous and iron-carbon alloys was created in USRIM (Kharkiv). The height of the continuous casting machine for non-ferrous alloys had a height of 1.75...2.5 m. This allowed the horizontal continuous casting machine to be positioned in almost any workshop of the machine-building complex during its reconstruction.

Disadvantages:

1. Cracks continued to appear on the surface of the billets even after the introduction of a new technology, both when exceeding the allowable productivity for

this stage of improving the continuous casting process, and when using secondary materials in the manufacture of billets.

2. It has been determined that the appearance of cracks is influenced both by the composition of the charge of the billet and the modes of operation of continuous casting machines.

3. As it turned out later, the HCCM cyclogram with a pause limited the productivity of machines at 0.5...0.3 m/min, in the production of billets of copper alloys with a diameter of 0.08...0.1 m and up to 0.4...0.8 m/min in the production of steel billets square size 0.15×0.15 m.

Let us accept the following assumption that the third and fourth stages of development conditionally began in the 1990s...2000s with a change in the frequency of movement of the billet in the mold. In work (Valuev, 2014, p. 200) it is reported that as of 2000, "The experience accumulated all over the world showed that at higher casting speeds ($V = 5.2$ m/min) the quality of cast billets is the same or even better than when casting at normal speeds. This work was done by «Voest-Alpine-Stahl» (VAS, Austria).

The third stage refers to the improvement of the process of continuous casting of billets from copper alloys in conditions of an increase in the frequency of movement of the billet, and the fourth stage refers to the improvement of the casting process of iron-carbon metals and alloys. These stages are very different from each other.

To increase the productivity of horizontal continuous casting machines, new mold designs and continuous casting methods were developed for the Karaganda Metallurgical Plant (Kazakh SSR). So, in the 80s of the last century, the following copyright certificates were obtained by the staff of the foundry department of the Kharkiv Polytechnic Institute (Shatagin et al., 1985). This method was conceived as a method and device for increasing the productivity of the HCCM from steel to points above 1.0 m/min.

Substantial efforts of specialists from USRIM were subsequently concentrated on developing the concept of horizontal continuous casting machines for metal, which became widespread in non-ferrous metallurgy. It should be noted that the experimental studies, which resulted in obtaining author's certificates (Sladkoshteev, Shatagin, & Vartazarov 1968a; 1968b), were carried out on a horizontal continuous casting machine built by USRIM specialists at the Karaganda Metallurgical Combine.

Until the 80s...90s in all countries the use of the continuous casting process was expanded. For example, in the work (Adno, 2001, p. 63), the author indicated that over the last 4 thousand years, more than 11 billion tons of ferrous metals were produced in the world, of which more than 80% were in 70 years of the last century. In support of this, it was shown in the work (Reshenie nauchno-tekhnicheskogo seminar, 1996) that the volume of billet production by continuous casting in various countries is: the United States – 88.9%; EU countries – 93.7%; in Japan – 96.9%, Ukraine – 8% and (3.5% worldwide).

Around the same time, the work was appeared that emphasized the advantage of horizontal continuous casting machines in comparison with vertical machines on the part of managers of large firms in the developed countries of the world. It is indicated that, as of 1990, in the world, horizontal machines were used to produce 68% of round billets from steel 0.08...0.12 m in size (Shatagin & Sladkoshteev, 1976, p. 24).

The theory of continual damage, expressed in the form of the Rabotnov-Kachanov equations (Kachanov, 1974, p. 15; Malinin, 1975; Rabotnov, 1966, p. 7), appeared in the second half of the last century. According to the classical Kachanov-Rabotnova theory, the current state of internal damage of a sample can be represented using a single scalar parameter (damage parameter) ω , which is a monotonically increasing function with time $0 < \omega < 1$. The damage parameter is interpreted as a relative reduction due to the effective, load-carrying area of the cross-section distributed within the micro defects sample. Material degradation is explained as a gradual decrease in the effective area, which actually carries a tensile load and determines the resistance of the specimen to stretching. Since the mechanics of Bailey and Norton worked in parallel, this law was named after all the authors: Bailey-Norton and Rabotnov-Kachanov.

As part of the second stage, studies were conducted on the issue: changes in the parameters of the damageability parameter of copper alloy billets when the frequency of the billet movement in the mold varies from 2.5 to 7.5 min^{-1} , taking into account that the cycle of the billet motion begins with a reverse movement. Experimental studies have confirmed that when using a cyclogram of the movement of billets according to the scheme «reverse motion – translational motion-pause», the damageability of billets is much lower than that of billets made on the same machine, but according to the cyclogram: «translational motion – pause». On the basis of this, a technological process of continuous casting of copper alloy billets was developed, which was protected by utility models (Khoroshylov, Ponomarenko, & Shatahin, 2006b; 2006c).

The essence of changes in technological operations, presented in the work (Breslavskij et al., 2008), was to exclude the effect of tensile forces in the cross-section of the billet due to changing the direction of movement of the billet during overcoming the FFR, and then there is a translational movement of the billet to a predetermined length. Thus, we obtain the following sequence diagram of the motion of the billet: “reverse - translational movement - pause”. To understand the process by which the damage parameter decreases, we turn to Fig. 5 which shows that when the billet moves with a frequency of 7.5 min^{-1} , the following change in the damage rate occurs with a different direction of the billet movement during the overcoming of the FFR.

Thus, in the work (Breslavskij et al., 2007) it was concluded that due to the implementation of the reverse movement of the billet in time to overcome the FFR and increase the frequency of advancement of the billets in the range of 2.5...7.5 min^{-1} , a new approach was created to reduce the damage parameter of copper alloys in the range of 0.3 to 0.1.

It is known technological process of improving the quality of the billets and the performance of a horizontal continuous casting machine under similar conditions

during continuous casting of steel, which could later become a useful prototype for improving the efficiency of continuous casting of copper alloy billets, when the cyclic movement of the billet in the mold is carried out according to the scheme: movement - reverse movement-pause".

The third stage of improving the process of continuous casting is based on the influence of the frequency of movement of the billet on its damage parameter, as well as on the influence of the direction of movement of the billet in time to overcome the FFR on the damage parameter. It was determined that for the frequency of movement of billets located in the range of 2.5...7.5 min⁻¹, the mechanical properties of the billet (temporary resistance to rupture) are influenced by the direction of movement of the billet during overcoming the FFR.

Based on the statistical processing of experimental data obtained as a result of the determination of creep, presented in (Horoshilov, Mel'nichenko, & Segal, 2017), in Fig. 6, dependences of the influence of the frequency of motion of the billet 1 and 2 are plotted, as well as the direction of its movement during overcoming the static friction force on the parameter of damageability of the billet (Breslavskij 1998; Breslavskij et al., 2008). In addition, Fig. 5 shows the effect of dependencies 1 and 2 on the mechanical properties of the billets (dependencies 3 and 4).

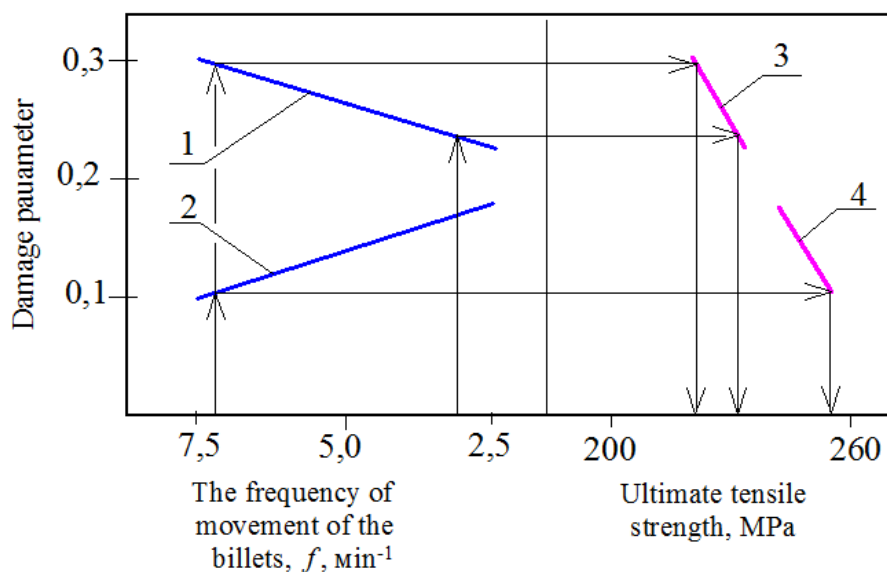


Figure 6. The effect of the frequency of movement of the billet with a diameter of 0.05 m on the parameter of its damage using reverse and progressive motion while overcoming the static friction force (Khoroshylov, 2013, p. 22): 1,2 –the dependence of the change in the value of the parameter of damage to the billet on the frequency of its movement in the mold during the progressive and reverse motion of the billet during overcoming the FFR; 3,4 - Dependences of the power limits while stretching the bronze billets of the BrT5Z5L5 on the damage parameter.

The dependencies shown in Fig. 5 allow us to make a comparative assessment of the change in the damage parameter for cyclograms created in the second and third stages of improving the process of continuous casting. So, according to the cyclogram created at the second stage (dependence 1), the billet in the cycle moves only progressively. With an increase in the frequency of movement of the billet from 2.5 to 7.5 min⁻¹, the parameter of damageability of the billet increases (dependence 1), and its mechanical properties decrease (dependence 3). Dependence 2 shows the change in the parameter of damage to the billet, provided that during the overcoming of the FFR it makes a reverse movement. Dependencies 2 and 4 indicate that increasing frequency of movement of the billet leads to the following processes:

- increase the parameter of damage to the billet from 0.224 to 0.3, while reducing the tensile strength of the billet under tension from 234 to 219 MPa;
- reduction of the damage parameter from 0.175 to 0.1, with an increase in the tensile strength of the billet under tension from 242 to 255 MPa;

Thus, the use of the element "swing" of the mold in the form of a reverse movement of the billet during overcoming the FFR while simultaneously increasing the frequency of movement of the billet from 2.5 to 7.5 min⁻¹ allows increasing the tensile strength of the billet under tension from 242 to 255 MPa.

Advantages:

1. As it follows from (Khoroshylov, 2013, p. 22), this improved continuous casting process allowed to increase the machine productivity by 25.5...56.3%, to increase the mechanical properties of the billet: temporary tensile strength by 12.4...15.8%.
2. LLC «Energoprom» is the enterprise where the patent of Ukraine No. 79415 was introduced in 2007, as well as the process of continuous casting in 2011.

Disadvantages:

1. There is no availability to conduct experimental studies on the manufacture of copper alloys billets with a frequency of movement of the billet from 60...120 min⁻¹ due to the lack of appropriate equipment (drive and non-friable crystallizer);
2. Low rates of increase in productivity HCCM and increase the mechanical properties of the billet.

Thus, during the work of the third stage we can draw the following conclusions:

1. The second stage began in 1995 with information about the possibility of increasing the frequency of movement of the billet in a horizontal mold. The stage ended with the improvement of the technological process of continuous casting of copper alloy billets, the implementation of the results of work in Energoprom LLC in Kharkiv in 2011, and the patent of Ukraine No. 79415 in 2007, in 2002 also in the Tsiboropteks enterprise in Dubai, UAE.
2. The reverse motion of the billet during the overcoming of the FFR eliminates the formation of micro-cracks at the initial moment of movement and further

development (microcracks) during the overcoming of the sliding friction force. This causes a decrease in the damage parameter, and the higher the frequency of movement of the billet, the more significantly the damage parameter decreases. So, at a frequency of 7.5 min^{-1} , the damage parameter (ω) with the reverse movement of the billet (technology of the second stage) was 0.1, and ω for the billet without reverse movement (technology of the first stage) was 0.3.

3. The development of new metal or metal-ceramic coating can contribute to the replacement of the graphite sleeve of the mold when casting copper alloy billets, in turn, this will increase the frequency of movement of the billet in the mold above 7.5 min^{-1} , which will significantly increase the mechanical properties of the copper alloys billets.

The fourth stage began with the creation of a project to improve the process of continuous casting of steel with a frequency of alternating movement of the billet to 150 min^{-1} , we will conditionally assume that this happened in 1995...2000 and is happening now. The fourth stage is not limited only by increasing the frequency of movement of the billet in the mold and monitoring the damage parameter of continuously cast billet.

The objectives of the fourth stage are the integration of all scientific, technical and technological solutions and regulation of the productivity of the continuous casting machine and the quality (mechanical properties) of blanks with high stability (reliability) of the machine.

By the fourth stage of improvement, the continuous casting process can be classified according to the following criteria.

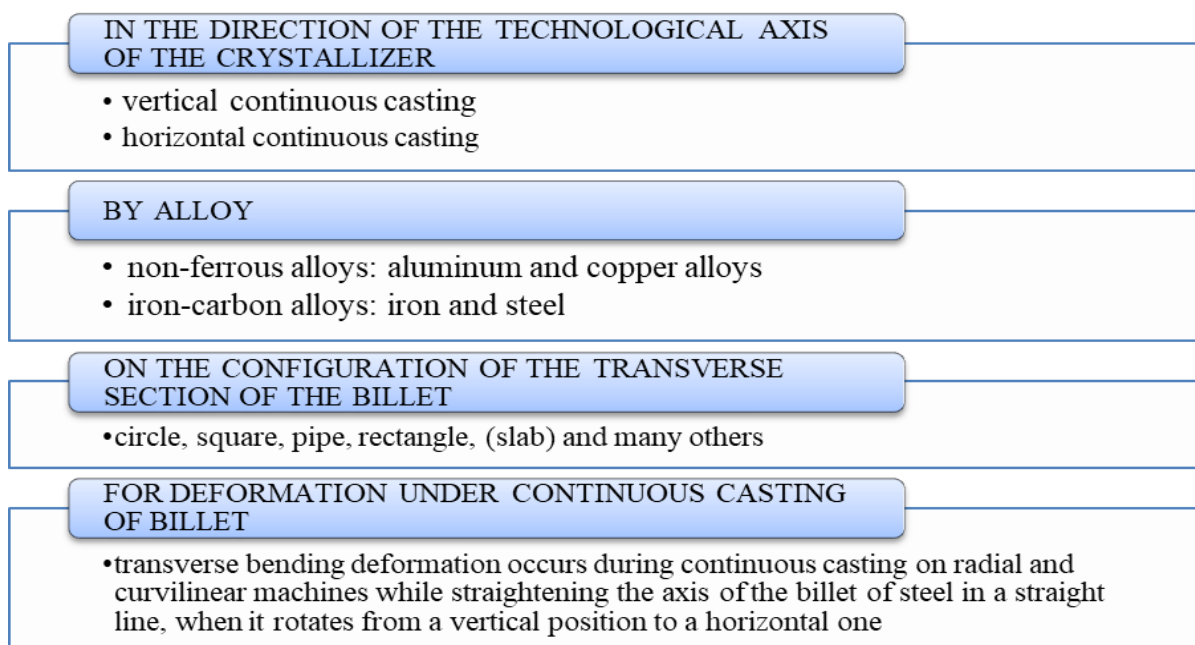


Figure: 7. Classification in the direction of the axis of the billet, by alloys, cross-section of the billet and the deformation to which the billet are subjected on radial and curvilinear machines.

For the further development of the fourth stage, specialists involved in continuous casting are working in various directions. For example, the author of (Verzilov, 2018, p. 20) investigated the stabilization of hydraulic processes in a vertical crystallizer, (Meshhaninova, 2000, p. 15) improved the technological process for the production of high-quality billets, (Andrianov et al., 2010; Gunenkov, Andrianov, & Prokhorenko, 2005) are working on the modernization of the steelmaking industry. Work (Mazumdar & Ray, 2001) is aimed at controlling the solidification of billets during continuous casting of steel. Much attention is paid to the control of the structure of the workpieces depending on the processing of melts (Narivskij, 2006, p. 24; Ukhin, 2012), as well as the change in technological parameters (Neklyudov, Sokolenko, & Netyosov, 2008). Significant results will be used to improve continuous casting productivity and improve quality.

The fourth stage is currently used for the continuous casting of iron-carbon alloys. The main objective of the fourth stage is reducing the damage parameter by increasing the frequency of the billet movement to the interval of 120...150 min⁻¹, as well as using inertial forces during alternating movement of the billet to mechanically affect the damaged parts of the forming billet, which leads to an increase in the linear productivity of the continuous casting machine with given mechanical properties of the billets.

An advertising article that appeared on the Internet resources from Spetsmash LLC reports the following: “We develop and manufacture continuous steel casting plants, which are new generation machines for domestic metallurgy. Our specialists have manufactured a drive that allows developing the frequency of cycles up to 120...150 per minute, according to the progressive “jerk – reverse stroke – pause” scheme that is used on almost all foreign machines, which made it possible to pour only high-quality carbon and low-alloy steels (Fig. 8).



Figure 8. Horizontal continuous casting machine for steel billets with a diameter of 0.08 m designed by LLC «SPETSMASH», commissioned in 2002–2003 (press release «SPETSMASH» LLC, 2005)

The advertising information from also reports on the performance of the HCCM, developed by them (press release «SPETSMASH» LLC, 2005). So, round and square billets with a diameter of 0.08...0.1 m have a linear capacity (V, m/min) – 2.5...4.0 m/min, billets with a diameter of 0.1...0.125 m are poured at a speed of 1.8...2.5 m/min, and billets with a diameter of 0.11...0.145 m – at a speed of 1.5...2.0 m/min. In recent years, we have seen that the world community has made clear progress in terms of the spread of the continuous casting process. There were publications from India, that in this country both non-ferrous and iron-carbon alloys are produced by continuous casting. This indicates the trend of moving the construction of new metallurgical complexes in the rapidly developing countries (Kumar, Suresh, & Van Swygenhoven, 2003, p. 5751; Yamaguchi, Sawai, & Nakashima, 2013, p. 17).

Each enterprise chooses the quality level of the billet, or the productivity of continuous casting machines. In 2010, for the future, the process of continuous casting of steel was being developed, which will allow us to have a continuous casting speed in the range of 0.5...0.8 m/min. In fact, this only indicates that these developers have a goal to significantly improve the quality of billets (Smirnov, 2010). A six-roll production line of square billets of 0.15×0.15 m made of steel was also launched at public company Arcelor Mittal Kryvyi Rih, and in 2019 another line of producing a 0.13×0.13 m square is expected. The average linear productivity of the machine when casting billets 0.15×0.15 m is 2.2 m/min, and the weight is 100 thousand tons per month (Press –release: «Arselormittal Kryvyi Rih», 2011).

In 1984 the thesis “Development of parameters of blues non-continuous casting machines with electromagnetic stirring for the production of billets of high-quality steel” was defended (Shifrin, 1984, p. 12).

And despite the fact that this dissertation work was defended before 2000, its theme is very consonant with modern tasks that metallurgical enterprises face: building bloom machines, using electromagnetic stirring with reversing the direction of the magnetic field. This work is aimed at the development of technological parameters of the bloom machines of the radial or curvilinear type. The development of technological parameters is complicated by the fact that the technological parameters must take into account the deformation processes that occur in curved sections of the trajectory of the billet (bloom). There are also dissertations made in the XXI century aimed at solving problems of improving the quality of continuously cast slabs during their casting from steel of wide grade composition (Shpak et al., 2008).

At the beginning of 2000, the production of steel billets began to develop rapidly, the essence of which was that this technological process by increasing the frequency of movement of billet from 60...90 to 150 min⁻¹ and cyclic reverse movement in the mold according to the scheme: "jerk-reverse -pause". This allowed increasing the linear productivity of HCCM from 1.0 to 4.0 m/min on a wide range of sizes. The speed of continuous casting of billets (slabs) is currently reaching 5.0...7.0 m/min. (Press – release: «SPETSMASH» LLC, 2005). It should be noted that the specificity of the thermal operation of the mold of a continuous casting machine is such that the smaller

the cross-section of the billet, the higher the casting speed and vice versa. Therefore, for billets of a size range, for example, of a circular section from 0.04 to 0.2 m, it can be in this range (5.0...7.0 m/min) of the linear productivity of the machine (Press – release: «Arselormittal Kryvyi Rih», 2011) Fig. 9. It should be noted that in the converter shop of Public company Arcelor Mittal Kryvyi Rih, the first continuous casting machine for steel square billets 0.15×0.15 m in size with a design capacity of 1.2 million tons per year was put into operation in the year (Press –release: «Arselormittal Kryvyi Rih», 2011). Figure 9 shows the machine.



Figure 9. A six-roll continuous casting machine for billets of steel 0.15x0.15 m in size at the converter shop of Public Company «Arselormittal Kryvyi Rih» (Press –release: «Arselormittal Kryvyi Rih», 2011)

Currently, two more continuous casting machines for steel billets with a section of 0.15×0.5 m and 0.13×0.13 m are being built. Supplier of basic equipment SMS Group (Germany). The design capacity of the second and third machines will be 1.2 and 1.4 million tons per year. Thus, we conditionally identified four stages of improving the process of continuous casting of billets from 1826 to the first quarter of the twenty-first century (Table 5.)

From table 5 it follows that data on the damage parameter are available only in those cases where they were determined. At the moment, these data are available only for billets from copper alloys obtained at the «Leninskaya Kuznitsa» plant and at «Energoprom» LLC. Such an effective damageability ($\omega=0.6...0.7$) of the billet, shown in Fig. 4, was obtained in conditions of non-stop traffic (Shatagin, Sladkoshteev, & Vartazarov, 1974, p. 76). An expert assessment of the damageability parameter was obtained 30 years after the experiment by O. A. Shatagin.

The table includes experimental data obtained on samples of copper alloys tested in the crystallization temperature range in the range (0.9...0.95) T_L for continuous casting processes related to the second and third stages, on the basis of which dependences 1 and 2 were constructed (Fig. 6).

Table 5. Indicators of linear productivity causing different values of the parameter of damageability of the billet and the stability of the continuous casting process

Years	Stages	Linear productivity (m/min) of billets copper alloys with a diameter 0,08 m, V, m/min, or for a square of steel 0.15×0.15 m		Parameter of damaging the produced billets, ω (According to fig. 6)	Stability of the continuous casting process
		Steel:			
1826...1960	First stage	Steel:	No data	No data	The process is not stable
		Copper alloys:	No data	(Expert review: 0.6...0.7) (Shatagin, Sladkoshteev, & Vartazarov 1974, p. 76), (fig. 4)	Cast from 0.2 to 9.2 m per casting
1960...1995	Second stage	Steel:	0.7...1.0 Karaganda Metallurgical Plant.	No data	The process is stable
		Copper alloys:	0.25...0.35 “Leninskaya Kuznitsa”, Kiev, (fig. 1)	0.225...0.31	The process is stable
1995...	Third stage	Steel:	No data	No data	No data
		Copper alloys:	0.3...0.5 «Energoprom», Kharkiv, (fig. 2) (Khoroshylov, 2013, p. 21)	0.1...0.175	The process is stable
1995...	Fourth stage	Steel:	2.5...4.0 4.0...6.0	No data	The process is stable

Despite the fact that damage data is available only for copper alloys for the second and third stages, we conduct an indirect assessment of the reduction of the damage parameter from stage to stage in terms of linear performance. So, if at the second stage of improving the continuous casting process, the average speed of continuous casting of steel billets with dimensions of 0.15×0.15 m was 0.8...1.0 m/min, then at the fourth stage, billets of the same size are cast in some cases at a speed of 2.5...4.0 m/min, and in other cases – 5.0...7.0 m/min. Also from the data presented in table 4, it follows that the fourth stage of improving the process of continuous casting causes a significant increase in linear performance.

Based on the foregoing, the rate of change in the process of continuous casting will increase. The following changes that improve the quality of the billets can be expected within 10–15 years. However, major changes in the design of the continuous casting machine will probably not be possible, since efforts can be directed at changing the specific qualities of the billet, which can only affect minor changes in the design.

Conclusions.

Based on the analysis of the stages of improvement of the billets, the stages of technological improvement of the process of continuous casting of iron-carbon and copper billets, we can draw the following conclusions:

1. It is shown that, indeed, each stage of the improvement of the continuous casting process is associated with a decrease in the damage parameter, which in turn led to an increase in the mechanical properties of the billets, which in turn increased the linear productivity.

2. It was determined that in addition to the non-stop (continuous) movement of the billets from 1826 to 2018, there were applied the following types of cyclic movement of continuously cast billets:

– alternating movement (“swing”) of the mold on vertical continuous and semi-continuous casting machines; on radial and curvilinear machines with a frequency of alternating movement of the mold up to $100...250 \text{ min}^{-1}$;

– the cyclic movement with the release of time for pauses according to the schemes: “translational movement – pause” and “reverse - translational movement - pause”; during the pause time, damaged parts of the billets (microcracks) are partially restored depending on the pause duration;

– cyclic alternating movement of the billet with a frequency of up to 150 min^{-1} using the inertial component of the movement.

3. It was determined that the mechanical properties of the billet increased on the one hand while reducing the frequency of the movement of the billet, i.e. according to the cyclogram developed at the second stage of the continuous casting process improvement. On the other hand, the mechanical properties of the billet increase:

– when increasing the frequency of movement of the billet in the range of $2.5...7.5 \text{ min}^{-1}$ and the reverse movement of the billet during the overcoming of the FFR (third stage);

– when increasing the frequency of movement of the billet in the range of $90...150 \text{ min}^{-1}$ and the translational movement of the billet during the overcoming of the FFR (fourth stage).

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Етапи технологічного вдосконалення процесу безперервного лиття залізовуглецевих і мідних заготовок

Анотація. У статті представлені етапи вдосконалення процесу безперервного лиття. Виявлено, що на кожному етапі технологічного вдосконалення процесу безперервного лиття відбувалося зниження параметра пошкоджуваності заготовки. Удосконалення процесу безперервного лиття дозволило на кожному етапі підвищити механічні властивості заготовки і продуктивність машин безперервного лиття. Перший етап, показаний як процес переходу кількості експериментальних напрацювань в якість, при якому лиття заготовок перейшло з нестабільного процесу в стабільний. Другий етап

охарактеризований створенням нових удосконалених процесів безперервного лиття. Так, крім існуючих машин вертикального типу були винайдені машини радіального, криволінійного та горизонтального лиття. До кінця ХХ століття цей варіант технологічного процесу вийшов на межу можливостей зростання якості заготовок і продуктивності машин безперервного лиття. Показано, що третій етап, призначений для безперервного лиття мідних сплавів і, був заснований на впливі частоти руху заготовки та реверсивного руху заготовки під час подолання сили тертя спокою. Визначено, що для частоти руху заготовок з мідних сплавів, що знаходиться в інтервалі $2,5...7,5 \text{ хв}^{-1}$ на механічні властивості заготовки впливає напрямок її руху під час подолання сили тертя спокою. Четвертий етап – обумовлює підвищення механічних властивостей заготовки за рахунок використання сил інерції при знакозмінному русі заготовки. Виявлено, що на четвертому етапі найбільш ефективно зросли механічні властивості заготовок, а лінійна продуктивність підвищилася від $0,4...0,8 \text{ м/хв}$ до $2,5...4,0 \text{ м/хв}$, а в деяких випадках до $5,0...7,0 \text{ м/хв}$.

Ключові слова: безперервне лиття заготовок; реверсивний і поступальний рух; мідні сплави; параметр пошкодження

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Этапы технологического совершенствования процесса непрерывного литья железоуглеродистых и медных заготовок

Аннотация. В статье представлены этапы совершенствования процесса непрерывного литья. Выведено, что на каждом этапе технологического совершенствования процесса непрерывного литья происходило снижение параметра повреждаемости заготовки. Усовершенствование процесса непрерывного литья позволило на каждом этапе повысить механические свойства заготовки и производительность машин непрерывного литья. Первый этап показан как процесс перехода количества экспериментальных наработок в качество, при котором литье заготовок перешло из нестабильного процесса в стабильный. Второй этап охарактеризован созданием новых усовершенствованных процессов непрерывного литья. Так, кроме существующих машин вертикального типа были изобретены машины радиального, криволинейного и горизонтального литья. К концу ХХ столетия

данный вариант технологического процесса вышел на предел возможностей роста качества заготовок и производительности машин непрерывного литья. Показано, что третий этап, предназначенный для непрерывного литья медных сплавов, был основан на влиянии частоты движения заготовки и реверсивного движения заготовки во время преодоления силы трения покоя. Определено, что для частоты движения заготовок из медных сплавов, находящейся в интервале $2,5 \dots 7,5 \text{ мин}^{-1}$ на механические свойства заготовки влияет направление ее движения во время преодоления силы трения покоя. Четвертый этап – обуславливает повышение механических свойств заготовки за счет использования сил инерции при знакопеременном движении заготовки. Выявлено, что на четвертом этапе наиболее эффективно возросли механические свойства заготовок, а линейная производительность повысилась от $0,4 \dots 0,8 \text{ м/мин}$ до $2,5 \dots 4,0 \text{ м/мин}$, а в некоторых случаях до $5,0 \dots 7,0 \text{ м/мин}$.

Ключевые слова: непрерывное литье заготовок; реверсивное и поступательное движение; медные сплавы; параметр поврежденности

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