https://doi.org/10.51885/3134-8009_JES_2026_2_12
SRSTI 53.03.11

CASTING AND ROLLING TECHNOLOGIES, CURRENT STATUS AND DEVELOPMENT PROSPECTS

ҚҰЮ-ПРОКАТТАУ ТЕХНОЛОГИЯЛАРЫНЫҢ ҚАЗІРГІ ДЕҢГЕЙІ ЖӘНЕ ДАМУ ПЕРСПЕКТИВАЛАРЫ

ЛИТЕЙНО-ПРОКАТНЫЕ ТЕХНОЛОГИИ, СОСТОЯНИЕ И ПЕРСПЕКТИВЫ РАЗВИТИЯ

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Keywords:
casting and rolling mills, metallurgy, rolling production, energy saving, continuous casting, deformation, metal structure.

ABSTRACT

The current development of metallurgical production is characterized by the search for new technological solutions aimed at increasing efficiency, reducing costs, and improving product quality. One of the most promising areas is the combination of continuous casting and rolling processes within casting and rolling units. These complexes allow the use of liquid metal heat, minimize the number of intermediate operations, and increase the productivity of metallurgical enterprises. The article analyzes existing solutions in the field of casting and rolling technologies, considers their advantages and disadvantages, and summarizes global and domestic experience in their implementation. Particular attention is paid to the problems arising during the operation of casting and rolling mills, as well as promising directions for their further development. The results obtained can be used in the modernization of existing enterprises, the design of new production facilities, as well as for educational and scientific purposes.

Түйінді сөздер:
құю-прокаттау орнақтары, металлургия, прокат өндірісі, энергия үнемдеу, үздіксіз құю, деформация, металл құрылымы.

ТҮЙІНДЕМЕ

Металлургия өндірісінің қазіргі заманғы дамуы тиімділікті арттыруға, өзіндік құнды төмендетуге және өнім сапасын жақсартуға бағытталған жаңа технологиялық шешімдерді іздеумен сипатталады. Ең перспективалы бағыттардың бірі құю-прокаттау агрегаттары шеңберінде үздіксіз құю және прокаттау процестерін біріктіру болып табылады. Бұл кешендер сұйық металл жылуын пайдалануға, аралық операциялар санын азайтуға және металлургиялық кәсіпорындардың өнімділігін арттыруға мүмкіндік береді. Мақалада құю-прокаттау технологиялары саласындағы қолданыстағы шешімдерге талдау жүргізілді, олардың артықшылықтары мен кемшіліктері қаралды, әлемдік және отандық енгізу тәжірибесі қорытылды. Құю-прокаттау орнақтарын пайдалану кезінде туындайтын проблемаларға, сондай-ақ оларды одан әрі дамытудың перспективалық бағыттарына ерекше назар аударылды. Алынған нәтижелер жұмыс істеп тұрған кәсіпорындарды жаңғырту, жаңа өндірістерді жобалау кезінде, сондай-ақ білім беру және ғылыми мақсаттарда пайдаланылуы мүмкін.

Ключевые слова:
литейно-прокатные станы, металлургия, прокатное производство, энергосбережение, непрерывное литьё, деформация, структура металла.
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АННОТАЦИЯ
Современное развитие металлургического производства характеризуется поиском новых технологических решений, направленных на повышение эффективности, снижение себестоимости и улучшение качества продукции. Одним из наиболее перспективных направлений является совмещение процессов непрерывного литья и прокатки в рамках литейно-прокатных агрегатов. Данные комплексы позволяют использовать тепло жидкого металла, минимизировать количество промежуточных операций и повысить производительность металлургических предприятий. В статье проведён анализ существующих решений в области литейно-прокатных технологий, рассмотрены их преимущества и недостатки, обобщён мировой и отечественный опыт внедрения. Особое внимание уделено проблемам, возникающим при эксплуатации литейно-прокатных станов, а также перспективным направлениям их дальнейшего развития. Полученные результаты могут быть использованы при модернизации действующих предприятий, проектировании новых производств, а также в образовательных и научных целях.

INTRODUCTION

The development of metallurgical production in the 21st century is linked to the need to increase energy efficiency, reduce production costs, and improve product quality. In this context, particular attention is paid to technologies that allow individual stages of the production cycle to be combined. One such direction has been the creation of continuous casting and rolling mills (CCRM), which combine the processes of continuous casting and hot rolling. Historically, the idea of combining casting and rolling processes arose at the beginning of the 20th century, but technical limitations long prevented its industrial implementation (Xu et al., 2020). It was only in the 1970s and 1980s that the first successful examples of CPS implementation appeared, primarily in the aluminum industry. Subsequently, the technology was also developed in steel production.

The metallurgical industry has traditionally been one of the basic industries ensuring the functioning and development of mechanical engineering, construction, energy, transport, and many other sectors of the economy. The key task of metallurgy is to produce high-quality metals and alloys with minimal resource and energy costs. In the context of global competition and increasing environmental requirements for production, this task is becoming particularly relevant (SMS Group, 2021).

The classic process for producing finished rolled products involves successive stages of metal smelting, casting into molds, crystallization, cutting ingots into billets, heating them in furnaces, and subsequent rolling. Despite the proven reliability of this approach, it is characterized by significant energy and time costs, as well as the high cost of finished products. In addition, such processes require large production areas and significant capital investments.

In the 20th century, continuous casting technologies (CCT) underwent significant development, enabling a substantial increase in the efficiency of metallurgical processes. However, even the use of CCT casting did not completely eliminate the gap between the casting and rolling stages: after crystallization, the metal requires additional heating and transportation, which entails additional costs (Lee & Park, 2021).

The solution to this problem was the introduction of continuous casting and rolling mills (CRM), which are integrated units that combine the process of continuous casting and subsequent hot rolling. CLR allow the heat of liquid metal to be used and eliminate a number of intermediate operations, which reduces energy costs, shortens the production cycle, and improves product quality.

The history of casting and rolling technologies spans more than a century. The first experiments combining casting and rolling date back to the late 19th century, but it was only with the development of materials science, thermodynamics, and automated control systems that the industrial implementation of these technologies became possible. Currently, CLR are used for the production of steel and non-ferrous alloys, providing a wide range of rolled and sheet products (Thompson & Bradley, 2019).

A progressive and highly efficient process for producing semi-finished products is continuous casting. The advantages of continuous casting of billets consist not only in a very significant reduction of the overall production cycle for obtaining finished metal and capital costs, but also in a substantial improvement in billet quality due to the uniformity of their structure and a sharp reduction in metal consumption.

The yield of acceptable slabs produced by continuous casting is approximately 20% higher for killed carbon steel and 10–12% higher for rimmed steel compared to ingot rolling on a slabbing mill. In continuous casting of steel billets without stopping the machine, known as "heat-to-heat casting," the yield of acceptable product increases to 99% due to the reduction of metal losses associated with machine stoppages. At the same time, the productivity of the casting machine increases significantly as a result of raising the machine operating time to 90–95%. The efficiency of continuous casting is also significant in the production of alloy steel.

By properly selecting the conditions of the crystallization process, steels of all grades and compositions can be cast on continuous casting machines, ranging from low-carbon rimmed steels to high-alloy steels. The process of continuous steel casting is readily automated. Continuous casting machines are divided into several main types (Figure 1) (Nippon Steel Corporation, 2019): vertical machines with transverse cutting of the semi-finished product in the vertical position (Figure 1a); vertical machines with bending of the cast metal and cutting in the horizontal position (Figure 1b); radial machines with a constant radius of curvature of the secondary solidification zone (Figure 1c); horizontal machines with single-sided (Figure 1d) and double-sided (Figure 1e) withdrawal of the strand.

The first continuous casting machines for steel billets that found the widest industrial application were vertical-type units. Liquid steel from the steelmaking ladle is fed into an intermediate tundish preheated to approximately 1200 °C. From the tundish, the liquid steel flows into the mold located below. In this mold, the starter bar serves as a movable descending bottom.

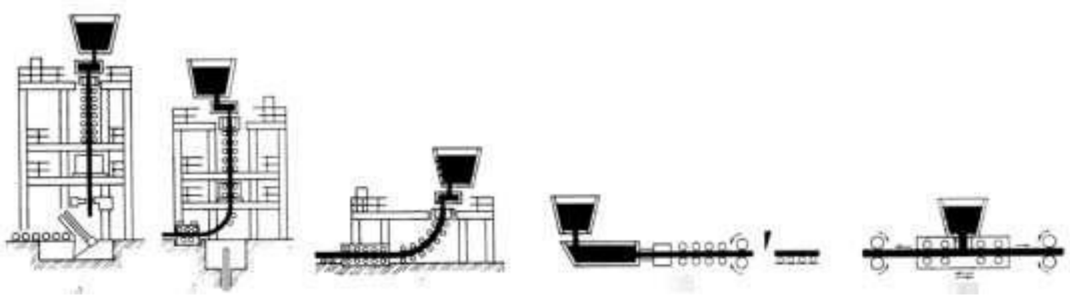
In the mold with copper walls, rapid cooling of the liquid metal occurs, resulting in the formation of a solid shell. The steel billet is formed in accordance with the dimensions of the mold.

The mold is continuously cooled by water circulating under pressure between its walls; at the same time, it performs a reciprocating vertical oscillation with an amplitude of 15–30 mm in order to prevent sticking of the liquid metal.

The steel solidifying in the mold adheres to the starter bar and is withdrawn downward by the pulling rolls. In the secondary cooling zone, the billet is cooled by water until complete solidification over the entire cross section. After that, in vertical-type machines, it is cut into measured lengths while remaining in the vertical position and then fed to the rolling mills.

The height of vertical-type continuous casting machines, which depends on a number of factors (billet cross section, chemical composition of the steel, withdrawal speed, and cut length), reaches 40–50 m, which requires high capital and operating costs. At the same time, it should be noted that vertical machines are the most versatile: they are used to cast a wide range of steel grades and to produce billets of various purposes and sizes; moreover, for casting billets of large thickness, they are the simplest and most convenient.

A specific feature of vertical continuous casting machines with bending of the cut billets is that, at the exit from the pulling rolls, the leading end of the billet is bent to the horizontal position, straightened, and cut into measured lengths in the horizontal position. This makes it possible to reduce the height of the machine, simplify the overall casting process, and increase its productivity. However, such machines require a large floor area and powerful equipment for billet straightening.



a *b* *c* *d* *e*

Figure 1. Types of continuous casting installations for billets

Note – compiled by the authors

Radial-type continuous casting machines appeared in the 1960s as a result of efforts to reduce the height of continuous casting installations and to create conditions for combining continuous casting and rolling of metal within a single complex. In this case, the mold and the guiding devices are curved along an arc with a constant radius. Experience has shown that billets produced on radial-type machines are in no way inferior in quality to those produced on vertical-type machines. At the same time, the height of radial continuous casting machines is significantly lower than that of vertical ones, which demonstrates their clear economic advantage (U.S. Steel Corporation, 2018).

On radial-type machines, higher casting speeds can be achieved due to variation in the length of the secondary cooling zone and a high degree of automation, and consequently higher productivity and improved quality of finished products. However, these machines also require large floor areas and powerful straightening equipment. It should also be noted that during straightening, the profile of cast billets is somewhat distorted, and surface cracks may appear on billets made from certain steel grades.

Continuous casting machines (CCMs) usually have several strands. In general, the number of billets cast simultaneously on vertical continuous casting machines, depending on the capacity of the steelmaking ladle as well as the cross section of the cast billet, may reach up to eight.

A further achievement in the development of continuous casting machines was the creation of horizontal-type machines (see Figure 1 d and e). Such machines have a height of no more than 8 m, do not require tall buildings, and significantly reduce shop construction costs. To stabilize the process of withdrawing metal from the mold, a method of producing two strands from a single mold is employed. Steel entering such a mold has two solidification fronts. As a result, structural and surface defects of the strand that occur during single-sided withdrawal are eliminated.

A highly promising method for improving the quality of metal produced on continuous casting machines is electromagnetic stirring of the metal during the crystallization process. This leads to a more uniform structure and a reduction in axial porosity of the strands.

Continuous casting machines produce slabs with cross sections of (120–250) × (900–1850) mm², blooms with a cross section of 280 × 280 mm², as well as billets of smaller cross sections. The casting speed ranges from 0.7 to 2.0 m/min. The productivity of continuous casting machines depends on the casting speed, the number of strands, and the range of produced cross sections.

At present, the problem of integrating continuous casting machines and rolling mills into a single complex is the main direction for improving the efficiency of the entire metallurgical production process. Solving this problem would make it possible to utilize the internal heat of cast billets, reduce metal losses due to oxidation during reheating in furnaces, and significantly decrease metal losses during billet cutting.

However, the implementation of integrated operation of continuous casting machines and rolling mills in a single continuous flow during the production of steel sections is extremely difficult (much more difficult than in the production of non-ferrous metal profiles), primarily due to the large difference between the exit speed of the cast semi-finished product from the continuous casting machine and the rolling speed of this product on the mills (U.S. Steel Corporation, 2018).

Full integration of continuous casting machines with rolling mills is possible by increasing the withdrawal speed of the cast billet from the machine, as well as by using special rolling mills as an intermediate link between the continuous casting machine and the finishing rolling mills. These mills operate at an entry speed corresponding to the speed of the continuous casting machine and provide high reduction ratios of 20–40 (planetary mills).

Integration of continuous casting of steel billets with rolling is possible when using multi-strand continuous casting machines equipped with several molds. In this case, the billets exiting the molds must be cut and fed sequentially into the rolling mill. Experience in the combined operation of continuous casting machines and rolling mills shows that, when producing finished sheets of varying widths, the most technologically efficient and economically justified solution is the use of slab molds with rapidly adjustable dimensions.

When casting slabs of constant dimensions while producing finished sheets of different widths, reducing devices are required, by means of which the slabs can be width-reduced to the required sizes (Salunkhe & Venkataraman, 2022). For slab width reduction and thickness reduction, reducing stands with vertical and horizontal rolls may be employed; these stands are installed downstream of the continuous casting machines.

The relevance of this topic is determined by a number of factors: the need to reduce energy consumption and production costs; growing demands on the quality of rolled metal products; the need to increase productivity while minimizing capital investments; and increased competition in the global metal products market.

The purpose of this work is to analyze the state and prospects of development of casting and rolling technologies in modern metallurgical production. To achieve this, we will consider: the main methods of combining casting and rolling processes; global and domestic experience in implementing LPS; the advantages and disadvantages of existing solutions; promising areas for technological development (Chernov, 2017).

Thus, the introduction of casting and rolling units into industrial practice is one of the key factors in the modernization of metallurgy, allowing it to increase its efficiency and competitiveness in the face of modern challenges.

MATERIALS AND METHODS

The methodological basis of this study is based on a systematic analysis of literary sources, patent information, the results of experimental and production tests of casting and rolling mills, as well as statistical data from leading metallurgical enterprises (Salunkhe & Venkataraman, 2022; Chernov, 2017). This comprehensive approach made it possible not only to summarize the accumulated global and domestic experience, but also to identify general patterns in the development of combined casting and rolling technologies.

The study used the following groups of materials: scientific publications in domestic and foreign journals devoted to the theoretical and practical aspects of the operation of casting and rolling mills; monographs and textbooks summarizing the fundamental principles of metallurgical processes; patent developments reflecting new technical solutions in the field of mold designs, rolling stands, and automatic control systems; reports from industrial enterprises containing data on the implementation of LPS and their operational characteristics; comparative studies published by international research organizations (Nalimov, 2010).

A set of methods was used to achieve the set goals: Historical and technical analysis was used to study the evolution of ideas for combining casting and rolling processes from the first experimental installations to modern industrial units. Comparative analysis made it possible to classify the methods of combination and identify their advantages and disadvantages. System approach - provided an opportunity for a comprehensive review of casting and rolling technologies, considering the relationship between equipment design, process parameters, and the quality of the final product; Generalization of experimental data - used to compare the results of LPS implementation in different countries and at enterprises of different capacities.

The efficiency of the continuous casting process for slabs, blooms, or other semi-finished products intended for subsequent rolling is well known. However, this efficiency increases even further when the casting and rolling processes are combined within a single unit or mill. The application of this technological process for producing rolled products by a continuous method directly from liquid metal opens up broad prospects for improving the efficiency of metallurgical production.

With this technology, it becomes possible to utilize the primary heat of the strand for deformation, eliminate intermediate storage of metal, and achieve complete continuity of the casting and rolling processes, which ensures a sharp increase in labor productivity.

The machines included in the aggregate for implementing this process become more compact; their weight and the required production area are reduced. Along with operational advantages, specific capital investments are also significantly reduced. Among the known methods of combining rolling with continuous casting, the following should be noted:1) liquid metal is fed directly into the roll gap; 2) the crystallization process begins separately from deformation, but rolling starts while the core of the strand is still in the liquid state; 3) rolling of the continuously formed strand is carried out after the completion of crystallization.

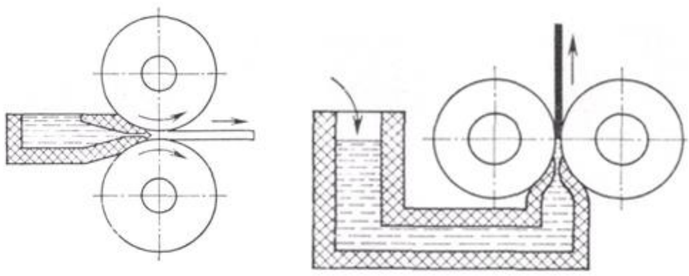
The first method was proposed by Bessemer and was called ingotless rolling; however, at that time it could not be practically implemented.

In the 1930s, pilot mills specially designed to develop this process for both non-ferrous metals and steel were built in the United States and the former USSR. However, positive results were not achieved, and the mills had to be dismantled. The main drawback of this method was the rupture of the metal shell formed at the very initial stage of contact between the liquid metal and the rolls, which caused structural inhomogeneity of the metal and other defects.

Subsequently, this process was significantly improved by feeding the metal not directly onto the rolls, but through guides installed between the rolls. This made it possible to stabilize the bite angle, which must be relatively small and constant.

In this form, the ingotless rolling process was successfully developed in two variants described below (Solovyov, 2022).

1. Liquid aluminum is fed through a distribution box into the roll gap formed by two horizontal rolls arranged one above the other (Figure 2a). Upon contact with the rolls, the liquid aluminum crystallizes, and the resulting strip exits the rolls continuously. Variant 1 is used at a number of plants in CIS countries for the production of aluminum strip in coils with a thickness of 8-12 mm, a width of 1030 mm, and a mass exceeding 2 t. The application of this technology instead of rolling strip from an ingot provided a substantial economic effect not only at the rolling stage itself, but also during subsequent processing of the coil due to the significant increase in its mass.



a	b

Figure 2. Diagram of continuous casting of aluminum strip:
a – with a horizontal crystallizer; b – with a vertical crystallizer

Note – compiled by the authors

2. The second variant of ingotless rolling differs from the one described above in that both rolls are arranged in the same horizontal plane, and liquid aluminum is fed into the roll gap from bottom to top, also through a distribution guide; however, in this case the guide is positioned vertically (Figure 2b). For the implementation of this process, several mills were built for the production of aluminum strip with widths of up to 1000–1600 mm and thicknesses of 3-8 mm. These mills are successfully operated at the Mikhailovsky and Kanaker aluminum plants, as well as at the Nachterstedt plant (Germany). The production cost of 1 t of aluminum sheet manufactured using Variant 2 is lower than that of Variant 1.

A slab continuous casting machine at the Keihin plant (Japan) is equipped with a device by means of which a slab containing a liquid phase is slightly reduced while passing through roller guides. This makes it possible to prevent the formation of axial segregation at the final stage of solidification. The slab width ranges from 600 to 2240 mm, and the thickness is 232 mm.

The second method is characterized by partial separation of the crystallization and deformation processes; however, since rolling begins while the core of the strand is still in the liquid state (Figure 3), the rolls are positioned close to the mold (Ivanov & Titov, 2021).

This method began to be applied several years ago in Austria for steel production using molds of the classical type with copper walls, along which the shell of the forming strand slides. This process makes it possible to eliminate the formation of a shrinkage cavity in the central part of the strand. However, in this case deformation occurs at the temperature corresponding to the transition of the metal from the liquid phase to the solid phase, when the plastic properties of the metal are very low. As a result, cracks may form in the central part of the strand; these cracks can be filled with the mother liquor enriched with alloying elements, which may lead to structural inhomogeneity of the strand. In addition, the mother liquor is displaced toward the trailing part of the strand, which will inevitably cause non-uniformity of the chemical composition along the strand length.

Despite this drawback, the described method has nevertheless found application in steel production. Thus, in Germany an installation has been built in which steel billets with a cross section of 160 × 160 mm are cast and then rolled without cutting in a continuous mill equipped with two horizontal and two vertical stands, reducing the section to 90 × 90 mm.

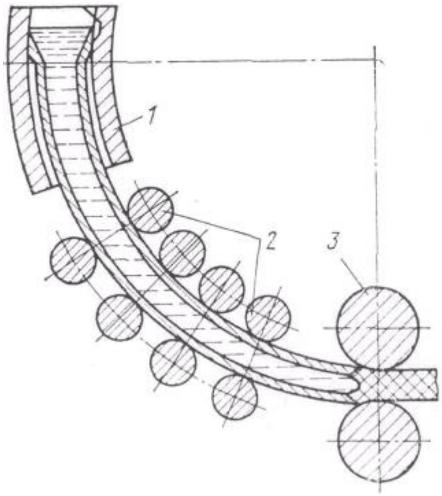


Figure 3. Schematic diagram of the combined process of continuous casting and subsequent rolling of metal in the two-phase state: 1 – mold; 2 – roller zone of secondary cooling; 3 – rolls of the first stand of the continuous rolling mill

Note – compiled by the authors

In recent years, there have been no reports on further dissemination of this method. For most steel grades, its application does not ensure high quality of rolled products. This method has also proven unsuitable for aluminum and other non-ferrous metals. However, it is очевидно that this process may occasionally occur in the ingotless rolling methods discussed above. If the peripheral speed of the rolls is increased, crystallization may shift into the deformation zone or even beyond it.

The third method consists in rolling the continuously formed strand after the completion of crystallization (Petrov & Loginov, 2020). Compared with the previous method, this approach provides the highest metal quality. In any case, rolling does not reduce the homogeneity of the continuously cast metal; its mechanical properties are improved and the possible product range is expanded. In research and in the practical implementation of results, this method has been adopted by VNIImetmash as the principal approach for combining rolling with continuous casting of aluminum, copper, steel, zinc, and other materials.

Data on the implementation of casting and rolling mills in various countries was used for analysis: Japanese enterprises (Keihin Works, Nippon Steel) - serial production of thin strips using a combination of casting and rolling; United States Steel (USA) - use of continuous casting machines with integrated rolling, providing a capacity of up to 20,000 tons/day; plants in Germany and Austria - use of planetary and forging-rolling units.

Thus, the materials and research methods represent a combination of theoretical analysis and generalization of practical experience in the operation of casting and rolling complexes, which ensures the objectivity and reliability of the results obtained.

RESULTS AND DISCUSSION

The development of casting and rolling mills (CRM) is a natural stage in the evolution of metallurgical production. The combination of casting and rolling processes is aimed at solving several key tasks at once: reducing production costs, reducing energy consumption, improving the quality of rolled metal, and shortening the production cycle (Nippon Steel Corporation et al., 2019, Chernov et al., 2017).

An analysis of patent and technical literature shows that in recent decades, the integration of continuous casting and hot rolling has become a priority. Unlike the traditional "casting - solidification - heating - rolling" scheme, the casting-rolling method eliminates the intermediate heating stage, allowing the use of crystallization heat. This significantly reduces energy consumption and increases the efficiency of the entire process.

The study showed that integrating casting and rolling processes provides the following advantages: Energy savings: using crystallization heat reduces fuel consumption by 20 - 30%; Shortened production cycle: eliminating secondary heating and intermediate storage reduces the cycle time by almost half. Reduced capital costs: continuous casting requires less space, fewer furnaces, and less auxiliary equipment. Improved metal structure: intensive deformation during crystallization contributes to grain refinement and improved mechanical properties. Production flexibility: a wide range of products can be manufactured, from thin strips to structural and shaped profiles (Fedorov, 2022,Thompson & Bradley, 2019; Nippon Steel Corporation, 2019).

Despite the obvious advantages, the implementation of LPS has revealed a number of problems that hinder their widespread use: The complexity of temperature control - any deviation from the optimal parameters can lead to the formation of cracks and internal defects; Limited thickness of the workpiece - continuous casting works most effectively with strip thicknesses of up to 70 - 100 mm. With larger sizes, difficulties arise with uniform cooling; High requirements for the quality of the source metal - the presence of non-metallic inclusions or variations in composition have a negative effect on rollability; Increased loads on equipment - the need to work with hot metal requires the use of materials with high thermal and wear resistance (U.S. Steel Corporation, 2018; Salunkhe & Venkataraman, 2022).

Industrial implementation examples. International experience.

Japan: Nippon Steel has developed industrial continuous casting machines for producing thin steel strips with a thickness of 2 - 3 mm directly from a liquid bath. The economic effect was manifested in a 25% reduction in energy costs and a 15% increase in productivity.

USA: U.S. Steel Corporation has implemented installations that integrate continuous casting and hot rolling. These complexes produce up to 20,000 tons of product per day, making them among the most productive in the world.

Germany: SMS Group is actively developing planetary rolling mills that allow the combination of casting and rolling of ingots wider than 1.5 m.

To evaluate the effectiveness of the CRM, a comparative analysis was conducted with the traditional "casting - heating - rolling" process (Table 1) (Petrov, Loginov, 2020).

Table 1. Comparative characteristics of the traditional production process and casting and rolling mills (CRM)

Indicator	Traditional scheme	CRM	Economic effect
Energy consumption, Gcal/t	1,2 - 1,4	0,8 - 0,9	25 - 30 %
Cycle duration, h	6 - 8	3 - 4	40 - 50 %
Equipment metal consumption	high	20- 25% lower	reduction in capital investments
Structural quality	heterogeneous	finer grain	improved properties
Productivity	standard	10- 15% higher	increase in output
Note – compiled by the author based on (Petrov, Loginov, 2020)			

The results of the analysis show that casting and rolling technology in most cases is more efficient and competitive compared to traditional technology.

An analysis of current trends allows us to identify several areas for improving the CRM:

1. Development of new mold designs that ensure more uniform cooling and reduce the risk of defects.

2. Use of high-temperature alloys and refractory materials to increase equipment reliability.

3. Automation and digitalization of processes - use of intelligent control systems to stabilize parameters.

4. Adaptation of continuous casting machines for the production of high-alloy and special steels required in the aviation, energy, and defense industries.

5. Combination with additive technologies - in the future, it may be possible to create hybrid production complexes where the billet is formed in a continuous casting machine and further processing is carried out using 3D printing methods.

The results of the analysis show that casting and rolling technologies have high potential for further development in metallurgy. Their implementation makes it possible to solve problems related to increasing energy efficiency, reducing production costs, and improving product quality. For the scientific community, it is important to identify the patterns of metal structure formation when combining processes, which opens up new avenues for research in the field of physical metallurgy and materials science.

Foreign experience (Japan, USA, Germany) demonstrates the high efficiency of LPS in the mass production of thin strips. Domestic experience also confirms the feasibility of using this technology, especially in aluminum production. A comparative analysis showed a 20-30% reduction in energy consumption, a nearly twofold reduction in cycle time, and a 10-15% increase in productivity (Kuzina & Arsentyev, 2021; Tarasov, 2019; Zaitsev, 2020).

Prospects for development are linked to improvements in mold designs, the use of new materials, the digitization of control systems, and the expansion of the product range to include high-alloy steels.

CONCLUSION

The analysis of the development and implementation of continuous casting and rolling mills (CRM) allows us to draw the following conclusions:

1. The combination of casting and rolling processes is one of the most promising areas of development in modern metallurgy. It reduces the energy intensity of production, shortens the production cycle, and improves product quality.

2. A comparative analysis has shown that the use of LPS reduces energy consumption by 20- 30%, shortens the cycle time by almost half, and increases productivity by 10-15% compared to traditional schemes.

3. Industrial experience with the implementation of LPS in Japan, the USA, and Germany has confirmed its high efficiency. Particularly significant results have been achieved in the production of thin strip and aluminum tape.

4. The main limitations of the technology are related to the need for strict temperature control, limited blank thickness, and increased requirements for the quality of the source metal. These problems are holding back the widespread use of CRM.

5. Promising areas for development include improving the design of crystallizers, introducing new materials for rolling mill working parts, digitizing process control, and expanding the product range by working with high-alloy steels and alloys.

6. In the long term, casting and rolling technologies are capable of occupying a key position in the metallurgical complex, ensuring the sustainable development of the industry by reducing

production costs and improving the quality and environmental friendliness of production. Thus, the results of the study confirm that casting and rolling mills are not only a technical but also a strategic solution that can determine the competitiveness of metallurgical enterprises in the global market.

CONFLICTS OF INTEREST: The authors declare that they have no conflicts of interest.

NOTICE ON THE USE OF ARTIFICIAL INTELLIGENCE TECHNOLOGIES: The authors of the scientific articles did not use artificial intelligence (AI) tools in the preparation of their works.

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