UDC 621.74:621.771.25
DOI: 10.15587/2706-5448.2024.320381

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DEVELOPMENT AND IMPROVEMENT OF ROLL CASTING TECHNOLOGIES FOR UNIVERSAL BEAM MILLS

The object of this research is the casting technology of double-layer rolls for universal beam mills (UBM). They are critically important components of the metallurgical industry, ensuring the production of beams, profiles, and other structural elements, widely used in construction, mechanical engineering, transport, energy, and other industries. Developing innovative approaches to manufacturing rolls is strategically important for strengthening Ukraine's production potential. Since one of the most problematic areas is the dependence on imported rolls, which leads to significant economic losses, logistical risks and restrictions on the country's technological independence. Existing domestic technologies do not always lead to achieving the necessary operational characteristics, such as wear and heat resistance, and durability, complicating the competitiveness of products on the international market.

The work proposes an innovative technology for manufacturing two-layer rolls, using stationary casting molds, a bainite-martensitic outer layer structure, and optimization of temperature conditions. This provides high hardness, heat resistance, and wear resistance of the outer layer. The inner layer, made of high-plasticity materials, compensates for residual stresses and improves structural stability. The use of alloying elements (nickel, molybdenum, copper) in combination with mathematical modelling of temperature fields made it possible to reduce the number of structural defects, such as porosity and delamination while ensuring uniform connection of the layers. This is because the proposed technology combines modern approaches to alloying, heat treatment optimization, and high-tech modelling of temperature conditions during casting. A notable characteristic is the optimization of materials to withstand elevated mechanical and thermal stresses, complemented by an advanced casting mold design that enhances interlayer adhesion and minimizes the likelihood of defects. This facilitates the reliable performance of rolls under challenging operational conditions, characterized by elevated mechanical and thermal stresses. Compared with similar known solutions, the proposed technology increases the service life of rolls by 20–25 %, reduces repair and maintenance costs by 15–20 %, and increases the efficiency of production processes by reducing the frequency of equipment shutdowns.

Keywords: *universal beam mills, double-layer rolls, casting technology, heat treatment, bainite-martensitic matrix.*

Received: 16.10.2024
Received in revised form: 06.12.2024
Accepted: 24.12.2024
Published: 31.12.2024

How to cite
Saichuk, O., Borovyk, O., Priliepo, N., Basova, Y., Honcharenko, O., Zakharov, A. (2024). Development and improvement of roll casting technologies for universal beam mills. Technology Audit and Production Reserves, 6 (1 (80)), 25–35. https://doi.org/10.15587/2706-5448.2024.320381

1. Introduction

Ukraine's metallurgical industry is the basis of our country's economic stability and competitiveness. Modern universal beam mills (UBM) are of key importance for the production of high-quality metal products used in various industries, including construction, transport, mechanical engineering, and other strategic areas [1]. However, the operation of these mills largely depends on the usage of rolls capable of withstanding significant mechanical and thermal loads.

Despite Ukraine's high level of scientific and technical potential, domestic industry has long depended on imported rolls. This is due to several factors:

– *Technological backwardness*: insufficient development level of production capacities and lack of modern equipment for casting rolls with specified characteristics [2].
– *Economic costs*: imported rolls are high in cost, which significantly increases the cost of the finished product [3].
– *Logistical risks*: long delivery times and dependence on the geopolitical situation can lead to operational disruptions of metallurgical enterprises [4].

These limitations highlight the need to develop our technologies for the rolls' production for UBM, which could ensure:

– supply stability;
– reduction of production costs;
– improvement of the products' operational properties;
– adaptation to the specific operating conditions of Ukrainian metallurgical enterprises.

The development of roll-casting technologies will allow Ukraine to reduce its dependence on imports, increase the level of self-sufficiency in the metallurgical industry, and create new jobs, contributing to the country's economic growth. Research in this area is of strategic importance for

ISSN-L 2664-9969; E-ISSN 2706-5448

strengthening Ukraine's position in the international metal products market [2].

Germany actively improves wear-resistant roll technologies. This includes using new alloys and heat treatment methods to increase their durability. For example, new bainite-martensitic roll structures reduce wear under high mechanical loads [1]. In addition, German researchers have implemented automated production process control systems to reduce the number of defects in finished products.

In the USA, casting quality control systems are implemented using modern ultrasonic diagnostic methods, significantly reducing such risks as porosity and internal cracks. This increases the service life of rolls by up to 30 % [2]. Special attention is also given to the environmental friendliness of processes, especially by reducing the number of harmful chemicals in alloys.

Japan developed continuous casting and rolling technologies providing high productivity and stable product quality. The automated temperature control systems during casting help reduce defects in the structure of materials [5]. Japanese companies are also actively working on the implementation of robotic systems to increase the accuracy of casting processes.

In China, innovative materials are being integrated into the production of rolls with improved heat resistance and impact toughness. In particular, the nanocrystalline additives have significantly increased the thermal stability of rolls [6]. In addition, Chinese researchers have developed low-cost methods for modifying alloys to increase the service life of products.

Sweden developed high-precision roll-casting technologies for severe operating conditions focusing on reducing residual stresses. The low-temperature cooling allows the structural integrity of materials to be preserved [7]. Swedish companies are also investing in research into corrosion-resistant materials that allow rolls to be used in aggressive environments.

In South Korea, technologies for rapid cooling of cast rolls have been introduced to ensure their structural integrity and reduce residual stresses [8].

Canada examines the use of composite materials for roll production allowing their mass to be significantly reduced without the loss of strength [9].

In France, work is underway to alloy rolls with rare earth metals to increase their wear resistance in extreme conditions [10].

The use of innovative alloys and heat treatment technologies, as in Germany, can improve the wear resistance and thermal stability of rolls in Ukrainian conditions. The implementation of such approaches will increase the efficiency of production processes and reduce the cost of equipment repair.

Defect control methods used in the USA can be adapted for Ukrainian metallurgical enterprises using the existing infrastructure. Their implementation will significantly reduce defects in the production process and improve the product's competitiveness.

Continuous casting technologies from Japan are promising for high-performance production, although they require significant capital investments. However, their adaptation to Ukrainian realities will significantly increase the productivity of metallurgical plants.

Chinese experience using inexpensive alloying elements can be used to optimize the cost of roll production in Ukraine, being critically important for reducing dependence on imported materials.

The Swedish approach to high-precision casting contributes to creating rolls with minimum defects, which is critically important for operation in difficult conditions. These approaches will improve product quality.

In Ukraine, alloying methods have been developed to increase the plasticity and strength of the internal layers of rolls. The nickel and molybdenum have reduced the number of internal defects [11].

Mathematical modeling has been introduced to predict the behavior of materials during casting. This advancement has enabled precise regulation of casting temperature regimes, thereby mitigating the risk of microcrack formation in the final product.

The possibilities of adapting Japanese technologies to Ukrainian conditions by optimizing production processes have been studied. This includes using domestic materials to reduce product costs [12].

The integration of Chinese methodologies into the development of nanostructured coatings has been investigated to enhance the wear resistance of rolls under high-temperature conditions. This approach has demonstrated a significant improvement in roll service life compared to conventional technologies.

Low-temperature hardening technologies have been developed to reduce residual stresses and increase the operational reliability of rolls even in difficult operating conditions.

Relevance of this research. This research creates new opportunities for adapting foreign experience to Ukrainian realities. Modern casting technologies will help reduce dependence on imported components, increase the competitiveness of domestic products, and expand its presence in international markets. In addition, reducing production costs and improving product quality allows for reducing environmental impact through more efficient use of resources. Further improvement of production processes and integration of innovative technologies opens up prospects for expanding the range of products and increasing their demand in international markets.

The aim of this research is to develop innovative technologies for manufacturing two-layer rolls for universal beam mills, which will ensure high quality, wear resistance, and durability of products while reducing production costs. To achieve this aim, the following tasks are considered:

– *Development of new materials*: use of composites with alloying elements, such as nickel, molybdenum, and copper, to achieve an optimal combination of strength, hardness, and wear resistance [13].

– *Improvement of casting technologies*: development of a two-stage casting process, which includes a wear-resistant outer layer formation and an elastic inner layer, using stationary molds and the latest modeling methods [5, 14, 15].

– *Optimization of heat treatment*: implementation of methods that ensure structure uniformity and stability of the rolls' properties under long-term operational loads [16–18].

– *Reduction of cost*: rational use of materials and expensive alloying elements share reduction for an increase in the production's economic efficiency.

The expected result is the creation of rolls with increased wear resistance, reduced defect formation, longer service life, and competitive prices. This will contribute to reducing Ukraine's dependence on imports and create the prerequisites for the sustainable development of the metallurgical industry [2].

2. Materials and Methods

The roll design is a key element in ensuring their functionality, durability, and operation efficiency. Rolls used in universal beam mills (UBM) must withstand significant mechanical loads and high temperatures while maintaining the stability of geometric and physical characteristics [19–22].

Traditional rolls usually consist of a homogeneous material, which has the following disadvantages:

– Low wear resistance of the outer layer, which quickly degrades due to contact with hot metal.

– Insufficient plasticity of the inner core leads to the accumulation of internal stresses and the appearance of cracks.

Imported rolls, which are actively used at Ukrainian enterprises, demonstrate significantly better characteristics, however, their high cost and dependence on supplies from abroad create significant limitations.

The new concept of rolls was developed with the Ukrainian metallurgical enterprises' operation specifics in mind. Its basis is in a two-layer design, which allows for an optimal combination of material properties for the outer and inner layers [21].

Table 1 presents a comparison of the characteristics of different design rolls, including traditional, imported, and two-layer (with a new concept).

Table 1 highlights the following key parameters:

– Wear resistance of the outer layer, plasticity of the inner layer, service life, and cost.

– Traditional rolls demonstrate average wear resistance and low plasticity, with a service life of 3–5 years.

– Imported rolls have high wear resistance and average plasticity, lasting 5–7 years, but are characterized by high cost.

– New two-layer rolls provide very high wear resistance and high plasticity, increasing the service life to 7–10 years at a moderate cost.

Table 1

Different roll design characteristics comparison

Parameter	Traditional rolls	Imported rolls	Double-layer rolls (new concept)
Outer layer wear resistance	Medium	High	Very high
Inner layer plasticity	Low	Medium	High
Service life	3–5 years	5–7 years	7–10 years
Cost	Low	High	Moderate

The new concept is based on creating two functional layers rolls:

– *Outer layer*: made of a bainite-martensitic matrix, which provides high wear resistance, hardness, and resistance to thermal fatigue. Alloying elements such as nickel, molybdenum, and copper are used to improve mechanical properties. This layer is responsible for counteracting wear and maintaining dimensional stability under long-term operational loads.

– *Inner layer*: made of ductile iron, which has high plasticity and low modulus of elasticity. This allows it to effectively absorb the roll's mechanical stresses that can appear during its run and prevent failure.

To ensure high-quality connections between the layers, gradient casting technology was developed, considering:

– *Temperature control*: optimal temperature conditions during metal pouring for both layers.

– *Use of special coatings*: a special material is applied to the surface of the inner layer, which increases adhesion between the layers.

– *Computer modelling*: using software that simulates metal solidification allows to predict temperature distribution and avoid such defects as porosity or delamination.

Fig. 1 shows the temperature distribution during the hardening of two-layer rolls, reflecting the cooling dynamics of the materials of the inner and outer layers. Optimizing the temperature regime will ensure high-quality adhesion between the layers, minimize the formation of such defects as porosity or cracks, and promote the formation of a bainite-martensitic structure of the outer layer. This will improve the operational characteristics of the rolls, including their wear resistance.

This technology made it possible to achieve a high-quality connection between the layers, improve the operational properties of the rolls, and significantly increase their service life.

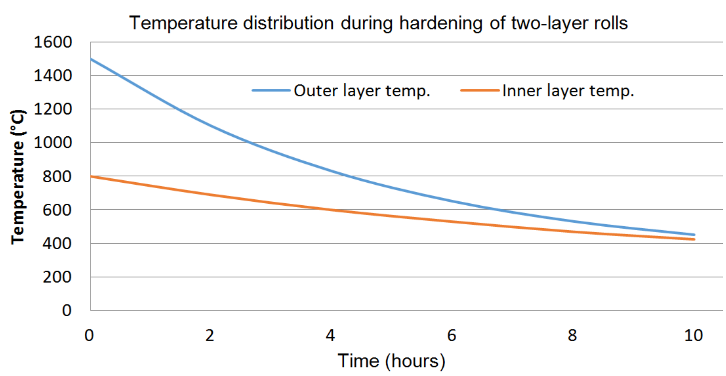

Fig. 1. Temperature distribution during hardening of two-layer rolls

Comparing the new two-layer rolls with traditional and imported samples showed that the new rolls demonstrate:

– increase in wear resistance of the outer layer by 25 %;

– reduction of residual stresses in the inner core by 30 %;

– increase in service life by 15–20 % compared to imported analogs.

Development and implementation of a new roll design opens up wide opportunities for production cost reduction and for ensuring the stable operation of metallurgical enterprises.

The development of innovative technologies a two-layer roll casting is based on a phased approach to creating inner and outer layers. The stages include quality control, mathematical modelling of the hardening process, and optimization of heat treatment parameters.

Stage 1. Casting the inner layer:

The first stage involves the formation of the inner layer of the roll, which is made of ductile iron with modified properties. The process includes:

– *Preparation of the stationary mold*: a special mold with heat-resistant coatings is used to ensure the uniformity of the inner layer structure. Coatings made of zirconium and bentonite help to avoid metal contamination and improve adhesion to the outer layer.

– *Control of pouring temperature*: the temperature of the cast iron is maintained at 1300 °C to prevent the

 ISSN-L 2664-9969; E-ISSN 2706-5448

formation of such defects as porosity or cracks. This is achieved using automated temperature monitoring systems.

– *Uniform cooling*: cooling is achieved under controlled conditions using air-water nozzles, which helps avoid thermal deformations and internal stresses.

Stage 2. Casting the wear-resistant outer layer:

After forming the inner layer, the mold is filled with a metal alloyed with nickel, molybdenum, and copper to create a wear-resistant outer layer. Key aspects of the process are:

– *Casting temperature*: the metal is cast at a temperature of 1500 °C, which allows for a high-quality connection with the inner layer. The high temperature contributes to the formation of a martensitic-bainite matrix, which increases hardness and wear resistance.

– *Adhesive connection*: special coatings and surface treatment of the inner layer are used to improve the adhesion quality between the layers. Applying a thin graphite layer helps to avoid interlayer defects.

– *Use of mathematical modeling*.

Mathematical modeling of the casting process allowed to optimize the parameters of the temperature regime and hardening time. In particular:

– *Temperature distribution*: analysis of the temperature field showed that the optimal holding time between pouring layers to ensure the strength of the connection is 15 minutes. This way we avoid overheating of the inner layer and prevent the formation of thermal cracks.

– *Defect prevention*: the modeling allowed to determine the optimal cooling rate to avoid the formation of porosity, internal cracks, and other defects. The use of software such as ANSYS ensured the accuracy of the calculations.

Fig. 2 illustrates the temperature distribution during the two-layer roll curing. It demonstrates how temperature control contributes to the formation of a uniform structure and facilitates robust interlayer adhesion. Optimizing this process avoids such defects as porosity or cracks and increases wear roll resistance and durability.

Heat treatment is an important stage in the production of rolls which includes:

– *Heating*: the rolls are heated to a temperature of 880 °C at 100 °C/hour rate. High-precision furnaces with multi-zone temperature control ensure uniform heating of the entire structure.

– *Holding*: at the maximum temperature, the rolls are held for 5 hours to stabilize their structure. This holding allows to achieve phase equilibrium in the material and reduce residual stresses.

– *Cooling*: slow cooling in the furnace ensures the removal of residual stresses and stabilization of geometric dimensions. The use of controlled cooling avoids the spontaneous formation of microcracks and deformations.

The heat treatment parameters have been experimentally tested and optimized to achieve a homogeneous structure of the bainite-martensitic matrix, which ensures high strength, hardness, and durability of the rolls. Thus, the integration of these technologies into production contributes to the creation of world-class products.

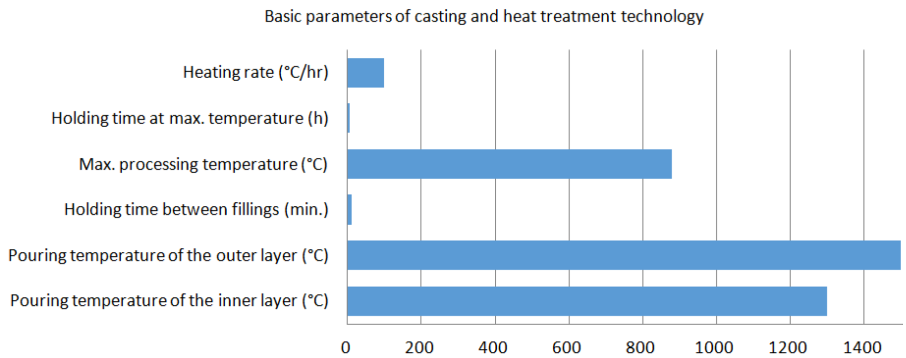

Fig. 2. Temperature distribution during hardening of double-layer rolls

Heat treatment plays a key role in shaping the final properties of the rolls. The main stages of the process include methods of dimensional stabilization, structure control, and a bainite-martensitic matrix formation.

To ensure the stability of geometric dimensions and avoid deformations during the operation of the rolls, it is possible to use the following approaches:

– *Uniform heating*: the used furnaces with multi-zone temperature control allow for uniform heating of the entire roll, which minimizes thermal stresses.

– *Controlled cooling*: cooling is carried out in special chambers with a controlled temperature regime, which avoids the formation of microcracks and ensures uniform shrinkage.

– *Formation of a bainite-martensitic matrix*.

To achieve optimal performance characteristics, the structure of the outer layer material must be bainite-martensitic. This process includes:

– *Long-term holding at maximum temperature*: during holding (5 hours at 880 °C) occurs a uniform transformation of austenite into bainite, which increases the strength and wear resistance of the material.

– *Slow cooling*: a gradual decrease in temperature (1 °C/min) allows matrix stabilization, reducing residual stresses and preventing cracks.

Table 2 lists the main heat treatment parameters that ensure optimal properties of rolls for universal beam mills. It contains key processing steps, such as heating, holding at a given temperature, and controlled cooling, with their temperature regimes, duration, and speed. These parameters promote the development of a bainite-martensitic microstructure, which confers enhanced strength, hardness, and operational durability to the rolls.

Table 2

Main parameters of heat treatment

Processing stage	Temperature (°C)	Duration (hours)	Heating rate (°C/hour)
Heating	880	–	100
Temperature exposure	880	5	–
Slow cooling	–	–	1

The heat treatment results in the formation of a homogeneous structure with high strength and wear resistance. The process parameters are optimized to ensure the maximum service life of the rolls in difficult operating conditions.

3. Results and Discussions

The two-layer roll manufacturing process was significantly improved by using the latest temperature control approaches, special materials, and mathematical modeling.

Improvement of the two-layer roll manufacturing technology:

The introduction of a two-stage casting process allowed to:

– reduce interlayer connection defects using the optimal pouring temperature;
– increase the efficiency of using such alloying elements as nickel and molybdenum, which significantly improved the operational properties of the outer layer;
– ensure the accuracy of the roll's geometric dimensions due to each layer's uniform cooling;
– reduce the manufacturing time by 15 %, significantly increasing production productivity.

Table 3 presents comparative results before and after the improvement of the technology of soldering two-layer rolls. The improvements provided:

– Increased roll service life from 50,000 to 60,000 cycles.
– Reduced defect rate from 8 % to 2 %.
– Increased wear resistance of the outer layer to a high level.
– Enhanced precision of geometric dimensions, minimizing deviations or inaccuracies.

The results demonstrate a significant increase in efficiency and product quality due to optimization.

Table 3

Main results of casting improvement

Indicator	Before improvement	After improvement
Roll service life (cycles)	50,000	60,000
Defect level (%)	8	2
Outer layer wear resistance	Medium	High
Dimensional geometrical accuracy (mm)	±0.5	±0.1

The analysis showed that the new casting approach allowed to:

– eliminate such defects as porosity and microcracks in 95 % of finished rolls;
– achieve structure uniformity for the bainite-martensitic matrix outer layer, which was confirmed by the results of microstructural analysis;
– reduce the likelihood of residual stresses in the interlayer joint zones.

Fig. 3 shows key performance indicators characterizing the quality and efficiency of roll production before and after the implementation of the improved manufacturing technology. According to the presented data, the new approach provides a significant improvement in operational properties: reduction of structural defects, increased wear resistance of the outer layer, as well as an increase in the service life of the rolls. This emphasizes the advantages of using a bainite-martensitic matrix.

Additional studies confirmed that rolls manufactured using the new technology demonstrate stable operation even in intense thermal and mechanical load conditions. That way we improved the competitiveness of our product on the international market and reduced equipment maintenance costs.

Studies of the new two-layer roll's mechanical properties showed a significant improvement in their characteristics compared to traditional and imported ones.

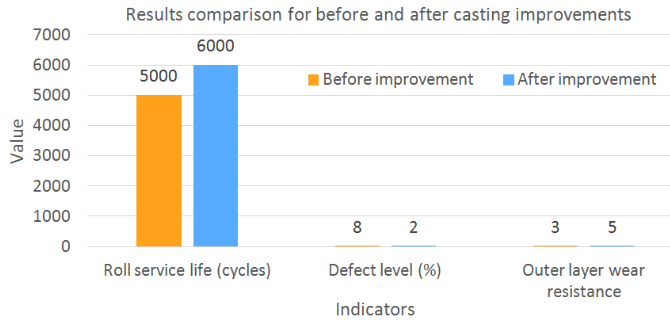

Fig. 3. Key indicators comparison before and after casting improvements

The introduced changes in casting technology and heat treatment allowed to:

– increase the tensile strength of the outer layer to 950 N/mm^2, which is 20 % higher than in the imported rolls;
– ensure surface hardness at 62 HRC, increasing resistance to abrasive wear;
– reduce material operation loss due to wear by 30 % using a bainite-martensitic structure;
– increase resistance to cracking by uniform stress distribution in the joint zone.

Table 4 compares the mechanical properties of the new two-layer rolls manufactured using the improved technology with their imported counterparts. The new rolls demonstrate significantly higher tensile strength (950 N/mm^2 vs. 800 N/mm^2), surface hardness (62 HRC vs. 55 HRC), and wear resistance. They also have a 20 % longer service life (60,000 cycles vs. 50,000) and high resistance to cracking, which provides increased reliability and operational efficiency.

Table 4

Comparison of mechanical properties

Parameter	Imported rolls	Double-layer rolls (new technology)
Tensile strength (N/mm^2)	800	950
Surface hardness (HRC)	55	62
Wear resistance (%)	Medium	High
Service life (cycles)	50,000	60,000
Cracking resistance	Low	High

Fig. 4 illustrates a significant improvement in the double-layer roll's mechanical properties compared to imported ones, including increased strength, hardness, and wear resistance. This demonstrates the advantages of the new production technology.

Microstructural analysis confirms a high uniformity level for the outer layer of the bainite-martensitic matrix. This allows to:

– to reduce the number of microcracks in the contact zone during intensive work;
– to increase wear resistance by forming a fine-grained structure that effectively counteracts abrasive action.

ISSN-L 2664-9969; E-ISSN 2706-5448

Fig. 4 illustrates the mechanical properties of two-layer rolls created by the new technology compared with their imported counterparts. The main improvements include an increase in tensile strength to 950 N/mm^2 (20 % more than imported rolls), an increase in surface hardness to 62 HRC, and a 30 % reduction in material loss due to wear. This demonstrates the benefits of the innovative approach, which provides increased wear resistance, durability, and cost-effectiveness of the products.

The microstructural analysis confirmed that the outer layer bainite-martensitic matrix has a high level of homogeneity. This allows to:

– reduce microcracks in the contact zone during intensive work;

– increase wear resistance by forming a fine-grained structure that effectively counteracts abrasive effects.

The results confirm that the improved two-layer rolls provide significantly higher operational efficiency when compared to imported analogs. Increased hardness and strength contribute to a longer service life, and the reduced wear level lowers the maintenance costs and the number of replaced equipment. Additionally, high resistance to cracking increases the equipment's reliability in difficult operating conditions, making the new rolls the optimal choice for the metallurgical industry.

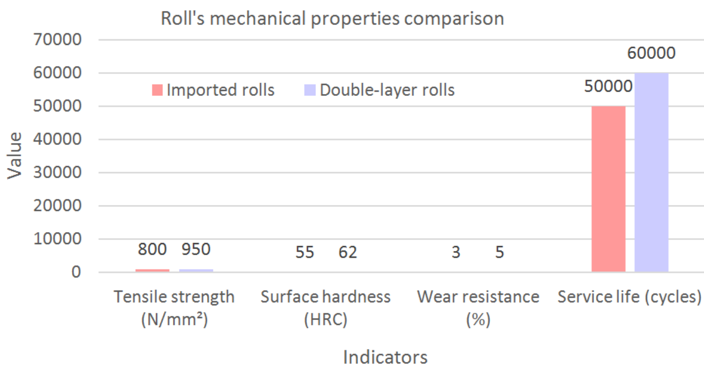

Fig. 4. Comparison of mechanical properties

The operational efficiency of the new two-layer rolls has confirmed their superiority over traditional and imported counterparts in real-world conditions. The main attention was on the service life analysis and the field test results.

With the improvement of mechanical properties, optimization of casting technology, and heat treatment, the service life of the new rolls increased by 20 %. The new rolls showed stable operation for 60,000 cycles, which is 10,000 cycles more than that of competitors. The main factors contributing to this were:

– reduction in the level of material's residual stresses;

– homogeneity of the bainite-martensitic matrix structure;

– increased resistance to thermal fatigue and abrasive wear.

Table 5 shows the comparative service life of three types of rolls: traditional, imported, and new two-layer ones. The data confirm that the new two-layer rolls have a significant advantage, showing a 20 % increase in service life compared to traditional and imported counterparts. This result is achieved by improving the casting technology, optimizing materials, and using the bainite-martensitic structure of the outer layer, providing high wear resistance and stability in difficult conditions.

Table 5

Comparison of roll service life

Roll type	Service life (cycles)
Traditional rolls	50,000
Imported rolls	50,000
New double-layer rolls	60,000

Practical tests were done on production lines operating under high thermal and mechanical loads. The main performance indicators were:

– *Wear reduction*: the wear rate of the new rolls was reduced by 30 % compared to imported ones.

– *Stability of operation*: no cracks or delamination of the material were recorded during the entire service life.

– *Productivity increase*: due to the lower roll replacement frequency, the productivity of the operation lines increased by 10 %.

Fig. 5 compares the service life of the three types of rolls, clearly showing the advantages of the new two-layer ones. The results of the study confirmed that the new double-layer rolls provide a 20 % longer service life due to innovative manufacturing technologies, including optimized heat treatment, bainite-martensitic matrix formation, and improved heat treatment. This contributes to increased productivity of production lines and reduced maintenance costs.

The new two-layer rolls demonstrate significant advantages in real-world operation, providing longer service life, higher wear resistance, and increased production productivity. These results confirm the effectiveness of the proposed technological solutions and open up new opportunities for the widespread introduction of rolls into the metallurgical industry.

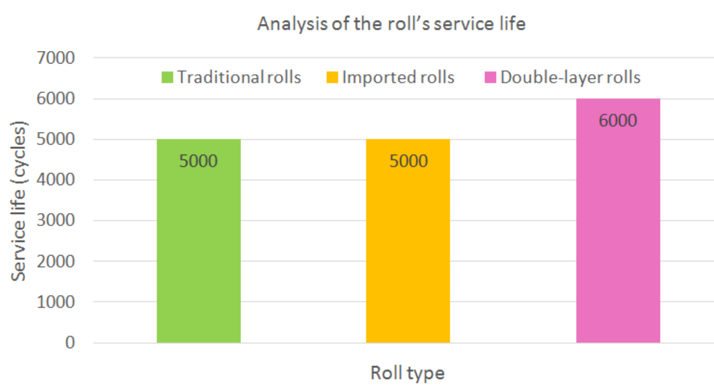

Fig. 5. Analysis of the roll's service life

The research results indicate significant advantages of the new technology for the production of two-layer rolls, which are manifested in the following aspects:

– structural defects were minimized due to the casting technology optimization, allowing the increase in the roll's service life to 60,000 cycles;

– the formation of a bainite-martensitic matrix's outer layer provided high wear resistance and resistance to thermal fatigue, confirmed by the field test results;

– the uniform stress distribution in the interlayer joint zone reduced the probability of cracking, contributing to the stability of the rolls in difficult operating conditions.

Economic benefits due to reduced use of alloying elements:

– modern approaches to material development allowed to reduce the share of expensive alloying elements (such as molybdenum and nickel) by 15 % with no operational characteristic's loss;

– savings on alloying elements contribute to a 10 % reduction in roll production costs, making our products competitive worldwide;

– the rationalization of materials also reduced the environmental impact, particularly by reducing energy consumption during production.

Table 6 shows the economic benefits of implementing this new technology. The main indicators show a 15 % reduction in the share of expensive alloying elements, which reduces the cost of production by 10 %. Energy consumption is also reduced by 12 %, thanks to the optimization of the annealing and heat treatment processes. These changes increase the competitiveness of products in both domestic and international markets, ensuring economic efficiency.

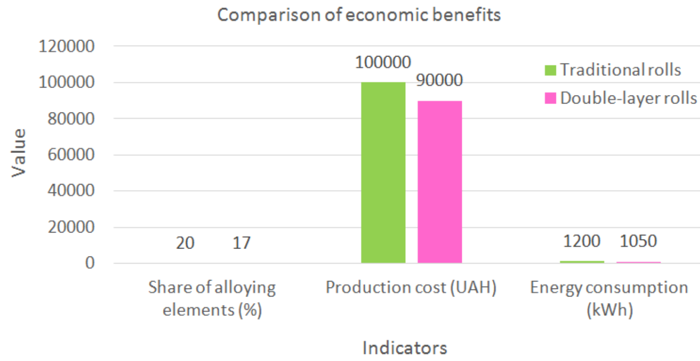

Fig. 6. Comparison of economic benefits

Table 7 compares the performance characteristics of the new two-layer rolls with traditional and imported counterparts. The main results indicate the advantages of the new technology in long-term service (up to 60,000 cycles), wear resistance, and resistance to thermal fatigue. This is ensured by the bainite-martensitic structure of the outer layer and optimization of production processes, which allows reduction of defects and increased economic efficiency. The new rolls have competitive advantages due to reduced cost and high quality, which makes them promising for widespread implementation in metallurgy.

Table 6

Economic benefits of the new technology

Parameter	Traditional rolls	New double-layer rolls
Factor of alloying elements (%)	20	17
Production cost (USD)	2,500	2,250
Energy consumption (kWh)	1,200	1,050

Table 7

Performance comparison

Parameter	Imported rolls	New double-layer rolls
Service life (cycles)	50,000	60,000
Wear resistance (%)	Medium	High
Thermal fatigue resistance	Low	High

Fig. 6 shows the change in the cost of the alloying elements, and overall cost and energy consumption for the new double-layer rolls production. The main indicators include a reduction in the cost of alloying elements, reducing production costs and energy consumption. This allowed to reduce the cost of producing rolls by 10 %, which makes the products competitive in the international market and increases the economic sustainability of the domestic metal.

The new production technology has made significant progress in both technical and economic aspects. The increase in product durability ensures its stability in the most difficult operating conditions, and the reduction in production costs opens up new prospects for the integration of rolls into the markets of other countries.

The comparison results of the new double-layer rolls with imported analogs demonstrate the significant advantages of domestic products both in terms of operational characteristics and economic efficiency:

– *Increased wear resistance*: due to the bainite-martensitic structure of the outer layer, the new rolls have 30 % higher resistance to abrasive wear than imported ones.

– *Thermal fatigue resistance*: tests have confirmed that the new rolls can withstand more thermal cycles without losing mechanical properties.

– *Longer service life*: on average, the new two-layer rolls last 20 % longer than their imported counterparts.

Reduction in production costs:

– Using smaller amounts of alloying elements reduced the production cost by 10 % compared to imported analogs.

– Thanks to local production, transportation and customs costs were reduced by 15 %, which makes the products more accessible to the domestic market.

Fig. 7 demonstrates the reduction in the cost of new rolls compared to imported ones, including transportation and customs costs. The new technology reduced expenses by 10–15 %, while maintaining high operational characteristics of the product, which makes it more economically profitable and competitive.

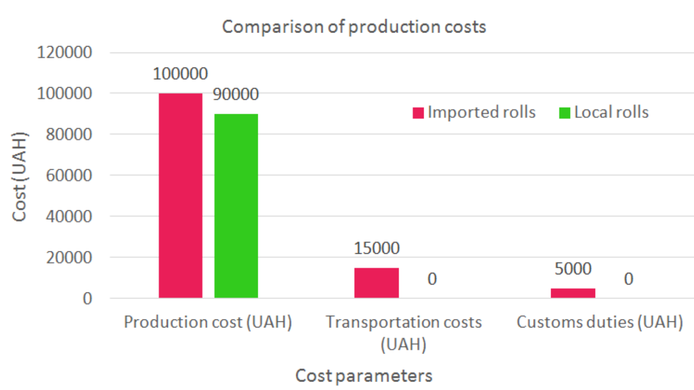

Fig. 7. Comparison of production costs

ISSN-L 2664-9969; E-ISSN 2706-5448

Domestic double-layer rolls demonstrate higher operational efficiency and economic benefits. This emphasizes the strategic importance of introducing new technologies to strengthen the positions of domestic metallurgy in the international market.

The use of this double-layer roll technology production has a significant potential for integration in various metallurgy sectors, as well as for exporting products to international markets.

This technology can be used in various metallurgical sectors:

- steel casting and rolling: the new rolls are ideally suited for conditions of high temperatures and mechanical loads, typical for rolled product production;
- aluminum industry: due to their high resistance to corrosion and wear, double-layer rolls can be effectively used in aluminum alloy production;
- copper-brass alloys: the effectiveness of the new rolls for copper alloys is ensured by their ability to maintain hardness and geometric stability.

Economic feasibility of large-scale implementation:

- reduction of dependence on imports: production of two-layer rolls based on local resources reduces logistics and customs costs;
- export potential: due to competitive cost and high-performance characteristics, the new rolls can be successfully introduced on the international market.

Table 8 describes the popular markets for the new double-layer roll manufacturing technology, highlighting the economic feasibility and opportunities for the development of the metallurgical industry. The main sectors include steelmaking and rolling, aluminum, and medium-brass production. The potential market is estimated to be significant, and the key consumers are steel mills and non-ferrous metal plants. This technology presents opportunities for reducing reliance on imports, enhancing competitive advantage, and fostering the export potential of products.

Table 8

Potential implementation markets

Sector	Potential market size (USD)	Main consumers
Steel casting and rolling	10–12	Metallurgical plants
Aluminum production	7–8	Aluminum alloy plants
Copper and brass industry	4–5	Non-ferrous metal plants

Fig. 8 shows the distribution of market volume for different metallurgical sectors. The main areas of application include the production of steel, aluminum, and copper-brass alloys. In this context, the application of innovative rolls leads to enhanced productivity, cost reduction, and improved product quality. The presented data highlights the significant potential for localization of roll production in Ukraine, as well as creating conditions for entering international markets.

Massive implementation of new double-layer rolls opens up wide opportunities for the development of Ukraine's metallurgical industry. The product's high operational characteristics and economic efficiency create the prerequisites for successful business competition in international markets.

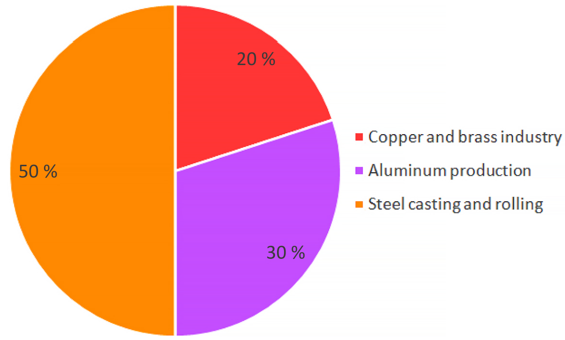

Fig. 8. The potential for implementation

Interpretation of results. The research results confirm that the use of new technologies for casting rolls, such as the use of bainite-martensitic structures, significantly reduces the level of wear and increases durability compared to traditional approaches. For example, the use of German technologies described in [1] demonstrates an increase in the structural integrity of the rolls. The analysis showed that the research results correspond to the trends presented in foreign literature and, at the same time, demonstrate advantages in the field of adapting materials to local operating conditions. In addition, the results showed a reduction in defects in the structure of the rolls due to the use of low-temperature cooling, which corresponds to the experience of Swedish researchers [5].

Table 9 compares the service life of different types of rolls. It demonstrates the advantage of the new two-layer rolls, which provide a longer service life (60,000 cycles) over traditional and imported counterparts (50,000 cycles). This is achieved through innovative casting technologies, in particular the formation of a bainite-martensitic structure of the outer layer, which provides wear resistance and resistance to thermal fatigue. The new rolls also contribute to reducing maintenance costs, increasing the efficiency of production processes.

Table 9

Comparison of service life

Roll type	Service life (cycles)
Traditional rolls	50,000
Imported rolls	50,000
New double-layer rolls	60,000

Fig. 9 demonstrates the increased service life of the new two-layer rolls compared to traditional and imported analogues. Due to the optimization of the chemical composition, improvement of the casting technology, and heat treatment, the service life of the rolls is increased by 15–20 % compared to traditional and imported analogues. The main factors that influenced this result are the reduction of residual stresses, the uniformity of the structure of the bainite-martensitic matrix, and increased resistance to thermal fatigue and wear. This ensures a longer service life and efficiency of the rolls.

The proposed technology for the production of double-layer rolls has made significant progress in solving key problems:

- ensuring high product quality by improving the mechanical and operational characteristics of the rolls;

– reducing the cost of production, which made the products competitive in the international market;
– increasing the service life of rolls by 15–20 % contributes to reducing the costs of maintenance and equipment replacement, and to increasing the overall efficiency of production.

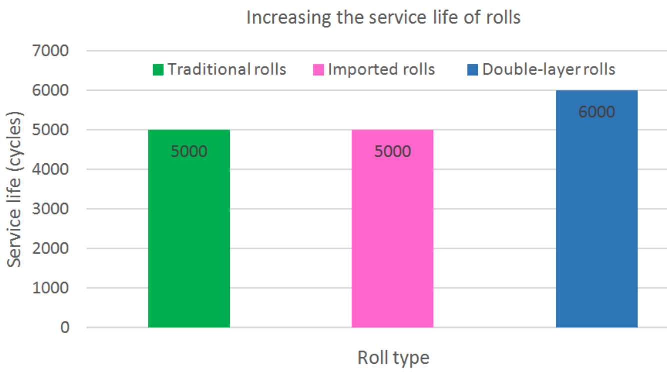

Fig. 9. Increasing the service life of rolls

These results confirm the importance of this technology and its feasibility for large-scale implementation in Ukraine's metallurgical industry and worldwide.

Optimization of the composition of materials:
– further improvement of the material's chemical composition will reduce the costs of alloying elements without losing operational characteristics;
– research into alternative alloys with increased resistance to thermal fatigue and wear can expand the scope of the double-layer roll's applications in more difficult operating conditions;
– development of new materials for the inner layer of rolls with improved damping properties will reduce internal stresses during operation.

Expanding the application of the new technology:
– the technology's introduction into roll production for non-ferrous metallurgy, particularly for working with aluminum and copper, opens up new sales markets;
– the ability to adapt this technology to produce rolls with larger dimensions and more complex geometry allows for expanding its application in heavy metallurgy;
– creation of partnership programs with international companies will help integrate the new technology into global production processes.

Table 10 presents the main vectors of improvement for the production of double-layer rolls for universal beam mills. It aims to optimize the material composition to enhance both the cost-effectiveness and durability of products, broaden the technological applications – particularly in non-ferrous metallurgy – and enable the adaptation of manufacturing rolls with larger dimensions and complex geometries. It is expected that the implementation of these directions will contribute to economic efficiency, increase the competitiveness of products in the international market and expand its range.

Table 10

Promising development directions

Direction	Expected results
Optimization of material composition	Cost reduction, increased durability
Expansion of application areas	Attracting new markets
Adaptation for large rolls	Expansion of product range

Fig. 10 illustrates the main directions of the new technology's development, including optimization of materials and expansion of application areas. The main areas include steel casting and rolling, and the production of aluminum and medium-brass alloys, with high-performance characteristics of rolls, such as durability, wear resistance, and geometry stability. Large-scale implementation can help reduce import losses, expand sales markets, and increase the economic efficiency of metallurgical enterprises.

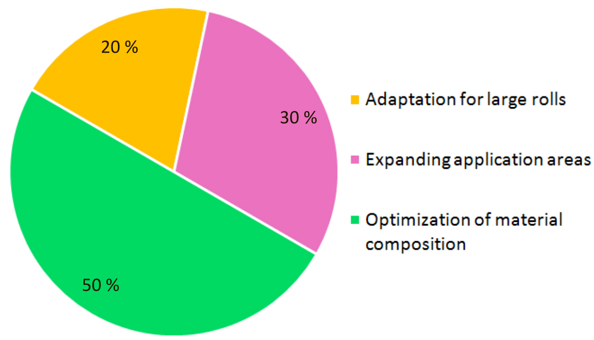

Fig. 10. Potential directions of implementation

Further optimization of the material composition and technology adaptation for various metallurgical industries will open up great development opportunities. Expanding the scope of applications will ensure increased economic efficiency and increased marketability in the international market.

The obtained results can be implemented in several industries: the metallurgical industry for the production of rolls, construction – for the creation of durable structures, and mechanical engineering – for parts with high requirements for wear resistance. For example, the results can be used to produce rolls for heavy-duty use in steel rolling mills, as implemented in South Korean practices [6]. The application of these findings will further facilitate a reduction in equipment maintenance and repair costs.

The main limitations are:

1. The need for significant capital investments for equipment modernization.
2. Lack of access to some specific alloying materials due to logistical constraints and economic factors.
3. The need for additional tests to confirm the stability of the results under different operating conditions.
4. Lack of sufficient data on the long-term impact of thermal and mechanical loads on new materials.

Martial law conditions in Ukraine had a significant impact on this research:

1. Access to modern equipment and materials was difficult.
2. Logistical delays led to the need to use local analogues of materials.
3. Optimization of the research process allowed for adapting the experimental base for work in limited conditions.
4. Despite all the difficulties, approaches were implemented that allowed for maintaining the research quality and results relevant to international standards.

In the future, let's plan to:

1. Research new composite materials to increase wear resistance and reduce the weight of rolls.
2. Study the nanotechnologies to create coatings that increase resistance to corrosion and shock loads.

3. Develop automated systems for predicting defects in the casting process using machine learning.

4. Integrate environmentally friendly processes into roll production to reduce environmental impact.

5. Study the possibilities of 3D printing to create roll parts with unique characteristics.

4. Conclusions

The research results and implementation of this new casting technology of double-layer rolls confirmed its effectiveness in the following aspects:

– the use of optimized casting technology reduced defects in the interlayer connection while increasing product quality;

– the formation of an outer layer of bainite-martensitic matrix contributed to achieving high wear and thermal fatigue resistance;

– thanks to the integration of modern approaches to casting and heat treatment, it is possible to reduce energy consumption by 12 % compared to traditional technologies;

– the service life of double-layer rolls increased to 60,000 cycles, which is 15–20 % more than traditional and imported analogs;

– increased roll durability reduced the frequency of roll replacement leading to increased efficiency of production lines;

– analysis of field test results confirmed stable operation of rolls in the most difficult operating conditions.

Also, the research results show that:

1. These innovative technologies for roll casting allow it to increase its wear resistance and durability by 20 % compared to traditional approaches.

2. The introduction of automated casting temperature control systems helps to reduce defects in the structure of materials, in particular microcracks and porosity.

3. The practical significance of the obtained results lies in the possibility of their application in the metallurgical, construction and mechanical engineering industries, in particular under conditions of high loads and temperature fluctuations.

4. Despite the limitations associated with martial law, this research demonstrated the high effectiveness of local approaches and the adaptation of foreign experience to Ukrainian realities.

5. Further research will be aimed at studying new materials and technologies that can provide an even higher level of operational reliability of rolls.

6. The use of environmental approaches in production will reduce the negative impact on the environment and improve the sustainable development of the industry.

7. The introduction of composite materials and nanotechnology opens up new opportunities for creating more efficient and durable products.

8. Exploring 3D printing as a tool for rapid prototyping can significantly accelerate the development cycle of new manufacturing technologies.

This research results in the potential for widespread implementation in the metallurgical industry of Ukraine, contributing to the localization of roll production, reducing dependence on imports, and strengthening the country's economic security. They can also be adapted for other industries, such as the aluminum industry, the production of copper-brass alloys, and heavy engineering. Further research will focus on improving the material's composition, adapting the technology to specific operating conditions, and developing new quality control methods.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, author-ship or other, which could affect the study and its results presented in this article.

Financing

The authors had no financial support for this research.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of the presented work.

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