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Enhancing the efficiency of the die casting process in metal molds

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ABSTRACT

Introduction. Die casting remains one of the most productive methods for producing complex thin-walled castings from aluminum alloys. However, typical problems of the process include subsurface gas porosity and the deterioration of product surface roughness due to the wear of the mold cavity surfaces. ***The purpose of the work*** is to conduct a comparative assessment of the effectiveness of various methods for strengthening the working surface of molds – traditional nitriding and the deposition of wear-resistant coatings by cathode-ion bombardment (*TiN* and multilayer *TiCN–TiN–MoN*) – to improve the quality of aluminum alloy castings. **Research Methods.** Experimental studies were conducted on "Handle"-type castings made of *AK7* alloy. The quality of castings obtained using molds with three types of protective surface coatings (nitriding, *TiN*, and *TiCN–TiN–MoN*) was evaluated based on the level of volumetric porosity (in accordance with GOST 1583-93) and the change in the roughness parameter *Ra* during durability tests (up to 100,000 casting cycles). **Results and Discussion.** It was established that the application of coatings using the *CIB* (cathode-ion bombardment) method statistically significantly improves the quality of castings compared to nitriding. The multilayer *TiCN–TiN–MoN* coating demonstrated the best results: a reduction in the maximum pore diameter by 58% and in their total number by 40%, which allowed the castings to be classified in the reduced porosity category (Grade 2 vs. Grade 3 for nitriding). Durability tests showed that the mold with a nitrided surface ensures acceptable casting roughness (***Ra*** ≤ 3.2 µm) for 75,000 cycles, while the molds with *TiN* and *TiCN–TiN–MoN* coatings maintain this parameter at ***Ra*** ≤ 1.6 µm up to 100,000 cycles. An important practical advantage of the *CIB* method is the significantly lower processing time of the deposition process (2–3 hours) compared to nitriding (20–30 hours), which reduces operating costs and equipment downtime. ***Conclusions.*** The application of the multilayer nanostructured *TiCN–TiN–MoN* coating deposited by cathode-ion bombardment is the most rational solution for increasing the service life of molds and improving the quality of aluminum alloy castings. This technology ensures a comprehensive improvement of key indicators (porosity, roughness) and offers significant economic potential due to the reduction in the duration of the mold strengthening process.

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Introduction

The intensification of competitive pressure inherent in the modern market compels companies to organize the production of goods that meet growing consumer demands while simultaneously minimizing costs. Pressure die casting is among the promising technological approaches for manufacturing products with enhanced performance characteristics; it is widely employed in the casting of non-ferrous metal products, such as those based on zinc alloys. This technology has gained widespread use in the production of window hardware, as it enables the precise replication of miniature parts characterized by complex geometries.

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Pressure die casting is one of the most widely used technologies, enabling the production of precision-shaped castings characterized by complex geometries and high fidelity in reproducing external features. The primary application of this method involves the manufacturing of aluminum alloy components, which account for up to **50%** of the total output produced via this method in certain countries. Despite its high precision and forming efficiency, this technology is characterized by a specific set of typical disadvantages. Chief among these are subsurface gas porosity – caused by air entrapment in the melt as it flows through the gating system – and surface layer defects, which manifest as significant roughness and gas blowholes [1].

According to regulatory standards, surface roughness is the primary parameter determining the surface quality of castings. Research indicates that surface quality degradation is caused by the wear of die components resulting from repeated mechanical and thermal loads occurring during the melt injection process.

Improving the quality of die surfaces and, consequently, reducing the roughness of pressure die-cast products can be achieved through one of two approaches: adjusting the technological process parameters or selecting tooling materials followed by thermochemical treatment. However, the former approach entails significant financial investment in research and development and the reconfiguration of the production complex. In contrast, the latter option often lacks economic efficiency due to the necessity of using expensive high-alloy steels. Under these conditions, nitriding represents the most cost-effective and technologically viable method of hardening treatment.

An alternative to traditional methods for enhancing the surface quality of dies is the application of modern processing technologies, including laser alloying, plasma irradiation, electron-beam modification, ion implantation, and magnetron sputtering. Despite the high efficiency of these technologies, their adoption in the foundry industry remains limited. In this context, the cathode-ionic bombardment method deserves special attention as a promising approach to improving the quality of forming surfaces.

Modern practice in modernization of foundry production is based on two primary approaches: the adjustment of technological process parameters and the optimization of tooling design. Among the controllable factors, the most significant influence on casting formation is exerted by the injection intensity, the magnitude of the applied pressure, and the thermal balance of the tool [2].

The filling speed directly determines the filling rate of the mold cavity. The production of castings with intricate geometries, including thin-walled and peripheral sections, necessitates the intensification of the melt feed rate. However, an excessive increase in speed risks the entrainment of air into the metal stream and the subsequent generation of volumetric gas defects [3]. As a result, a situation frequently arises in practice requiring a trade-off: to ensure complete mold filling, a certain level of porosity or surface degradation in the finished casting is permitted.

Pressure magnitude is a critical factor for ensuring structural uniformity and the compliance of the casting with specified density requirements. The literature provides standards for establishing the minimum required force specific to the geometry of the parts being produced [4]. It should be noted, however, that the implementation of calculated optimal parameters is not always feasible due to the limited technological capabilities of the casting equipment currently in service.

The establishment of a stable thermal regime during casting depends on a complex of interrelated conditions. These include the temperature parameters of the molten metal, which are influenced by its composition, as well as the thermal state of the tooling, which is determined by the tool steel grade, the methods of thermochemical hardening applied to the working surfaces, and the composition of the release agents and lubricants employed [5]. It should be noted that the allowable range for metal temperature adjustment does not exceed 10 °C, and the standard material for die manufacturing is *0.4 C-5 Cr-Mo-V-Si* steel, which is typically nitrided. Consequently, achieving a balanced thermal casting regime requires labor-intensive iterative calculations and experimental trial-and-error testing, which increases both the lead time and the cost of production preparation.

Contemporary research demonstrates a diverse array of solutions focused on enhancing the performance properties of aluminum castings manufactured via pressure die casting. However, the implementation of any of these existing technologies encounters objective technological barriers and necessitates substantial financial investment and time resources for testing cycles and the fine-tuning of production parameters.

In such circumstances, the development of an innovative methodology for modifying the properties of aluminum castings that exhibits minimal sensitivity to variations in casting process parameters is of particular relevance. A key advancement in this field is the use of hardening coatings based on nitride and carbonitride phases, applied to the forming die components via vacuum ion-plasma deposition [6].

Additional technological solutions that facilitate improved casting quality include vacuum-assisted die casting [7] and the oxygen die casting process [8–12]. The primary objective of these methods is to minimize the gas phase within the die cavity. However, the implementation of these approaches entails a radical re-equipping of the production line and the establishment of additional safety systems, leading to a significant increase in capital expenditures.

According to experimental findings [13–19], the deposition of a multilayer *TiCN-TiN-MoN* structure onto the working surfaces of casting dies used in the production of aluminum castings via cathode-ionic deposition can significantly improve the characteristics of the finished products. The mechanism underlying this positive effect is attributed to a combination of factors, the most critical of which are the minimization of friction forces at the melt–die interface and the optimization of heat dissipation during die operation.

In addition to the aforementioned method, alternative approaches to the application of protective layers exist. Research presented in [20–23] indicates that the application of a metallic layer to the die surface can enhance the overall efficiency of the pressure die casting process for non-ferrous metals and alloys, resulting in castings with improved quality and an extended service life. Tungsten and tungsten carbide were selected as the coating materials in these studies. However, these works do not establish a clear correlation between specific deposition methods and the resulting quality indicators of the castings. Furthermore, they lack a targeted analysis of the specific requirements and challenges inherent to the pressure die casting of aluminum alloys.

According to the results presented in scientific studies [24–29], the ion implantation of chromium and molybdenum shows significant potential for surface property modification. Nevertheless, the practical application of this methodology is hindered by several technological limitations, the primary ones being the formation of a coating with insufficient thickness – which adversely affects abrasive wear resistance – and the high complexity of the deposition process itself.

Experimental studies detailed in [12] demonstrated the potential of metal-ceramic composite coatings. While these materials are characterized by high microhardness, thermal stability, and nanoscale thickness, they simultaneously exhibit critical performance limitations. The latter include a susceptibility to brittle fracture and insufficient adhesive strength, both between dissimilar coating layers and at the interface with the die material substrate.

Thus, modern manufacturing possesses a wide array of technologies for depositing metallic coatings onto the working surfaces of casting tooling. Nevertheless, the large-scale industrial adoption of these developments is hindered by a combination of techno-economic barriers. The most significant of these include insufficient adhesion to the substrate material, the technological complexity of deposition processes, inadequate wear resistance, a susceptibility to brittle fracture, and strict requirements regarding the minimum thickness of the formed layer.

The purpose of this study is to perform a comparative analysis of the effects of various die surface hardening methods – conventional nitriding and the application of wear-resistant coatings (*TiN* and multilayer *TiCN-TiN-MoN*) via cathode-ionic bombardment – on the key quality indicators of aluminum pressure die castings.

To achieve the stated purpose, the following ***tasks*** were addressed:

− experimental evaluation of porosity: to conduct a comparative analysis of the extent and nature of porosity in castings produced using dies with nitrided surfaces versus those protected by ***TiN*** and ***TiCN-TiN-MoN*** coatings.

− surface roughness investigation: to determine the effect of the protective coating type on the surface roughness of the castings and to track the evolution of this parameter as a function of the number of die operating cycles.

− comparative analysis of service life: to evaluate and compare the service life of dies with various protective surfaces based on the criterion of maintaining the required casting quality.

Research Methodology

To confirm the working hypothesis regarding the relationship between the application of hardening coatings deposited via cathode-ionic bombardment (*CIB*) and the improvement of cast part properties, an experimental testing program was implemented. The primary objective of these tests was to compare the degree of porosity and the surface roughness of the finished castings. Two groups of samples served as the subjects of the comparative study:

– Samples produced using dies with *CIB* coatings: monolayer *TiN* (3 µm) and multilayer *TiCN–TiN–MoN* (6 µm);

– Samples manufactured using the baseline technology with a nitrided *0.4 C-5 Cr-Mo-V-Si* steel die, where the thickness of the hardened layer was 100 µm. This nitriding method is accepted as the standard practice in pressure die casting.

The selection of hardening methods with significantly different layer thicknesses (nitriding ~100 µm, monolayer *TiN* ~3 µm, and multilayer *TiCN–TiN–MoN* ~6 µm) is justified by their industrial relevance. These thicknesses correspond to the typical processing parameters used in manufacturing for each respective method. The comparison was conducted under conditions that closely mimic real-world operation, where layer thickness is an inherent characteristic of the technology. The objective of this study was not an isolated comparison of the properties of layers with equal thickness, but rather a comprehensive evaluation of competing technological solutions in their standard industrial implementations.

The deposition of *CIB* coatings was performed via a *VU-1BS* vacuum system using the cathodic sputtering method, in which the coating material was evaporated from a cathode target and deposited onto the die surface, which acted as the anode. The process parameters are provided in Table 1.

Table 1

Process parameters for protective coating deposition

Parameter	**Value**
Ultimate residual pressure in the vacuum chamber	$5 \times 10^{-3} – 4 \times 10^{-3}$ Pa
Preheating of the **die** surface and the coating fixtures	300–340 °C
	20–30 min
Argon pressure in the vacuum chamber	$4 \times 10^{-2} – 3.5 \times 10^{-2}$ Pa
Source solenoid current	4 A
Anode voltage	1,200–1,300 V
Steady-state anode current	0.12–0.15 A
Substrate cleaning (via **evaporator** activation)	3 min
Bias voltage	100–150 V
Process gas pressure	$6 \times 10^{-2} – 5 \times 10^{-2}$ Pa
Deposition time	20 min

A “Handle” casting made of *93 Al-7 Si* (*GOST 1583-93*) aluminum alloy was selected as the object of study. This choice was motivated by the propensity of the thick sections in this specific configuration to form gas porosity. The critical geometric characteristics of the casting included a maximum wall thickness of 15 mm and a mass of 0.1 kg (Fig. 1).

The technical specifications for the product established stringent requirements for the surface finish (roughness not exceeding ***Ra*** 3.2 µm) and mechanical strength (the ability to withstand a torque of up to 25 N·m without permanent deformation).

The porosity level was determined in accordance with the parameters specified in the *GOST 1583-93* standard, which regulates the placement of the reference microsection in the central portion of the casting.

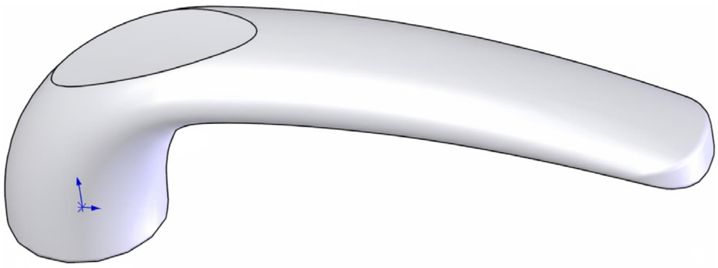

Fig. 1. “Handle”-type casting

Since aluminum pressure die castings typically exhibit a shift in maximum pore density to a specific depth beneath the surface [14], the methodology was modified to include serial sectioning to identify the layer with the highest defect density. The sample preparation procedure, also prescribed by *GOST 1583-93*, involved milling along the zone of expected maximum porosity (within the casting volume), followed by the preparation of three macrosections with an area of 1 cm^2 each and a surface roughness of $\boldsymbol{Ra} \leq 1.6$ µm (Fig. 2) . Quantitative assessment of structural defects was performed via visual analysis by recording the number of pores and their diameters, followed by ranking on a 5-point scale, where the minimum score indicates negligible porosity and the maximum score indicates a critical concentration of defects.

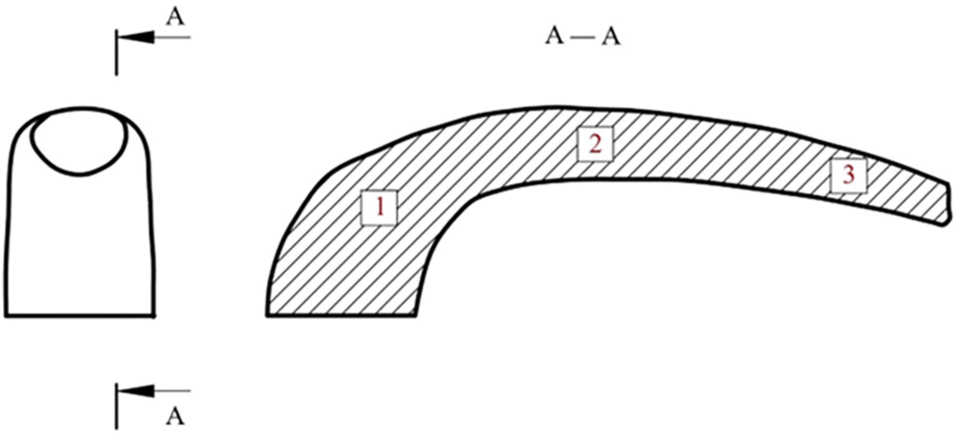

Fig. 2. Cross-section of the casting for porosity determination

Surface roughness was determined using a *Mitutoyo SJ-210* contact profilometer equipped with a 2 µm radius diamond stylus. To minimize systematic error caused by the orientation of the casting relative to the gates, the final ***Ra*** value was determined by averaging the results of three separate measurements taken at different points on the sample surface.

For each experimental zone, $\boldsymbol{n}$ = 3–5 replicates were performed. Results are presented as the arithmetic mean ($\boldsymbol{x}$) ± the 95% confidence interval. The standard deviation ($\boldsymbol{s}$) and confidence intervals were calculated using standard formulas of mathematical statistics. The statistical significance of differences between groups was determined using a two-sample *t*-test with unequal variances ($\boldsymbol{p} < 0.05$) .

To ensure the statistical significance of the data, a comparative analysis was performed on castings produced during different melting cycles. The prescribed technological casting parameters included: the use of *93 Al-7 Si* aluminum alloy (*GOST 1583-93*), a melt injection speed of 5 m/s, an injection pressure of 80 ± 8 MPa, a water-based tooling cooling system, a clamping force of 300 ± 15 kN, a four-cavity die configuration, a melt temperature range of 660–670 °C, and a tool preheating temperature of 130–150 °C.

Results and Discussion

The developed multilayer *TiCN-TiN-MoN* coating exhibits a range of performance advantages tailored to the specific conditions of aluminum pressure die casting. Critical characteristics of the composition include: resistance to chemical interaction with the melt, a low friction coefficient ($\boldsymbol{f}$ = 0.26–0.28) , a thin-film thickness (3–10 μm) that eliminates the need for tooling geometry adjustments, a multilayer structure, and enhanced fracture resistance due to the alternation of layers with varying hardness and significant residual compressive stresses. An additional advantage is the formation of strong diffusion bonds at all interfaces: between successive coating layers and at the interface between the base layer and the die material [6].

The combination of these properties leads to a reduction in the *Reynolds* number, which minimizes the formation of turbulent eddies in the molten metal within the most problematic areas of the mold. These zones include fillet transitions, regions located opposite the gating channels, and narrow cavities. The resulting laminar flow reduces the amount of entrapped gas porosity within the casting body, ultimately exerting a positive influence on its structural integrity and performance characteristics.

The physical mechanism underlying the positive effect of the multilayer *CIB* coating on casting quality is multifaceted:

– friction reduction and improved mold filling: the low friction coefficient ($\boldsymbol{f}$ = 0.26–0.28) and high surface finish of the coating minimize adhesive interaction at the melt-tooling interface. This promotes laminar flow (confirmed by a decrease in the *Reynolds* number), reduces air entrapment, and ensures more complete filling of thin die features.

– heat flow management: the multilayer structure, featuring alternating layers with different thermal conductivities (*TiCN*, *TiN*, *MoN*), creates an adjustable thermal barrier. This facilitates more uniform heat dissipation from the casting surface, thereby reducing thermal stresses and decreasing the risk of hot tearing.

– chemical inertness: the coating acts as a barrier that prevents diffusion and chemical interaction between the active aluminum melt and the die steel, which directly reduces the probability of surface defect formation.

The layer-by-layer analysis of the macrostructure (Fig. 2) revealed a zone of maximum pore defect concentration within the depth range of 1–4 mm from the external surface of the casting. Based on this established pattern, a standardized depth of 3 mm, corresponding to the region of most pronounced porosity, was selected for subsequent investigations (Fig. 3).

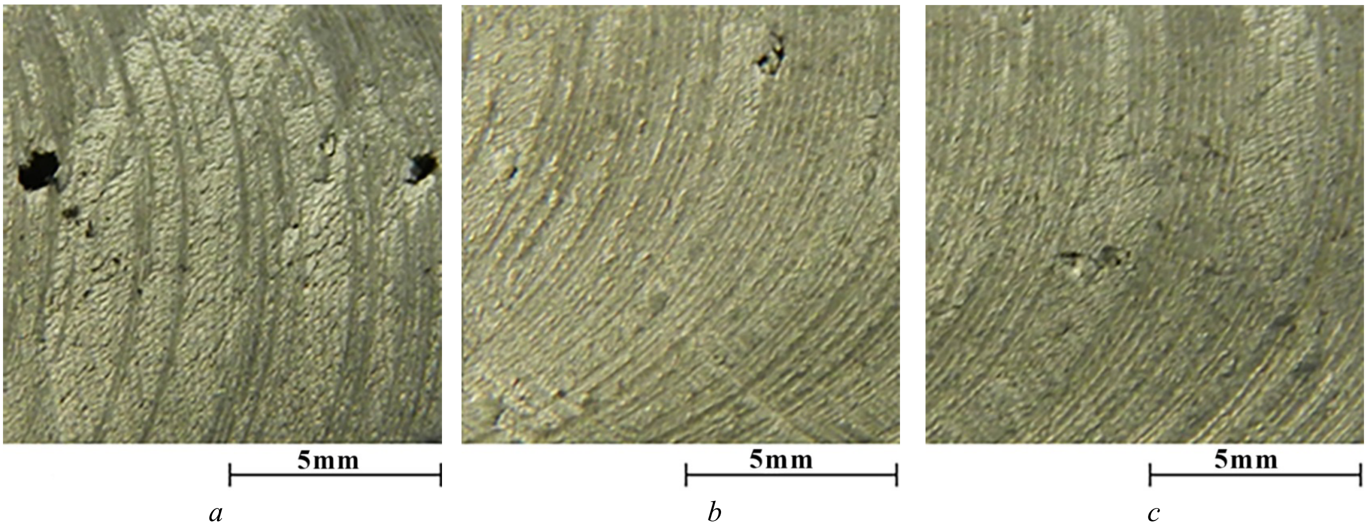

Fig. 3. Macrosection of the "Handle"-type casting produced in a die with:
a – a nitrided surface; *b* – a *TiN* coating; *c* – a *TiCN–TiN–MoN* coating

According to the research results (Table 2), samples produced in nitrided dies correspond to Grade 3 of the adopted porosity classification, representing a moderate defect level. At the same time, products obtained using tooling with coatings deposited via cathode-ionic bombardment exhibit improved structural characteristics, specifically a reduction in the maximum pore diameter and a decrease in the total pore count. This allows them to be categorized as Grade 2 samples with reduced porosity.

It should be noted that macrosection No. 1 exhibited the highest level of porosity. This is attributed to the melt flow characteristics in this zone – specifically the change in flow direction – as well as the increased wall thickness of the part in this cross-section.

Table 2

Porosity indicators of the castings

Surface treatment of the mold cavity	Macrosection No.	Maximum pore diameter (mm)	Number of pores	Porosity grade according to *GOST 1583-93*
Nitriding	1	0.9	15	4
	2	0.5	11	3
	3	0.6	8	3
TiN coating	1	0.4	10	3
	2	0.2	6	2
	3	0.2	4	2
TiCN–TiN–MoN coating	1	0.3	8	3
	2	0.2	6	2
	3	0.2	5	2

The surface roughness of the castings remained stable across all monitored areas, not exceeding ***Ra*** 0.8 μm during the initial stage of die operation, regardless of the treatment method applied to the tool's working surface.

During the first 50,000 operating cycles, the mold surface coating technology did not demonstrate a significant effect on this parameter; however, with a further increase in the number of shots, the difference in the roughness values of products obtained using different treatment methods increased noticeably (Fig. 4).

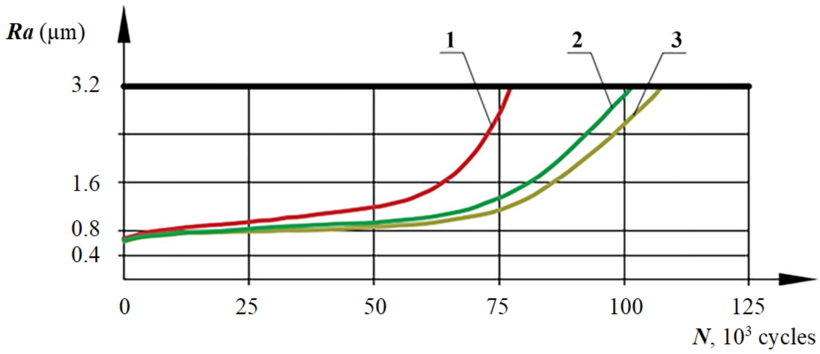

Fig. 4. Roughness values of castings produced in dies with:
1 – a nitrided surface; *2* – a *TiN* coating; *3* – a *TiCN–TiN–MoN* coating

Durability tests showed that upon reaching 75,000 operating cycles, the surface roughness of castings produced in a nitrided mold reached a critical threshold of ***Ra*** 3.2 μm. In contrast, samples obtained using coatings applied by cathode-ionic bombardment maintained an ***Ra*** value that was, on average, half that level. The analysis leads to the conclusion that a nitrided mold maintains acceptable surface quality for 75,000 cycles, whereas tooling treated with cathode-ionic bombardment ensures compliance with roughness requirements for up to 100,000 operating cycles. A comparative assessment also revealed the advantage of the multilayer *TiCN–TiN–MoN* system over the monolayer *TiN* coating in terms of overall performance characteristics.

Techno-economic analysis shows that applying wear-resistant coatings via *CIB* offers both technological and economic advantages over traditional nitriding. While equipment capital costs are comparable, the labor intensity of the *CIB* process (2–3 hours) is an order of magnitude lower than that of nitriding (20–30 hours), leading to reduced operating costs and shorter mold downtime. The multilayer *TiCN–TiN–MoN* coating, combining high wear resistance with low application time, is recommended for production in series as the most rational solution to reduce casting production costs while simultaneously enhancing quality.

Conclusions

Based on the study conducted, it was established that the application of wear-resistant coatings via cathode-ionic bombardment statistically significantly reduces the volumetric gas porosity of castings compared to traditional nitriding. The multilayer *TiCN–TiN–MoN* coating proved to be the most effective, reducing the maximum pore diameter by 58% and the total number of pores by 40%. This allows the resulting castings to be classified as having reduced porosity (Grade 2 according to *GOST 1583-93*, versus Grade 3 for nitriding).

It has been proven that coatings applied via the *CIB* method ensure lower and more stable surface roughness (***Ra***) values throughout the entire tooling lifecycle. A mold with a nitrided surface ensures compliance with roughness requirements **(*Ra*** ≤ 3.2 μm) for 75,000 cycles, whereas tooling with *TiN* and *TiCN-TiN-MoN* coatings maintains this parameter at ***Ra*** ≤ 1.6 μm for up to 100,000 cycles, demonstrating a two-fold improvement in the roughness criterion.

Thus, the application of the multilayer nanostructured *TiCN–TiN–MoN* coating is the most technologically justified method for extending the service life of molds. This coating, combining a low coefficient of friction, chemical inertness, and high adhesion, not only improves the quality characteristics of the castings but also increases the durability of the tooling itself. Collectively, this significantly enhances the efficiency of the die casting process compared to nitriding and monolayer *TiN* coating.

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Conflicts of Interest

The authors declare no conflict of interest.

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