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ENHANCING THE SERVICE LIFE OF FERROCHROME CASTING LADLES USING PROTECTIVE REFRACTORY COATINGS

Abstract. Lining wear of casting ladles is a key challenge in high-carbon ferrochrome production, leading to reduced service life and increased operating costs. This study presents a laboratory and pilot-industrial evaluation of protective refractory coatings during tapping of ***FeCr*** 800–850 ferrochrome. Coatings based on chamotte, quartzite, and secondary materials with various binders were investigated. Liquid glass was found to exhibit poor adhesion, whereas a combined binder system (cement – bentonite – organic additive) demonstrated the highest stability. Chamotte-based coatings increased ladle service life to 13–18 heats (compared to 10 in the baseline regime), quartzite coatings showed a moderate effect, while slag-based coatings were ineffective.

Key words: *high-carbon ferrochrome, casting ladle, refractory lining, service life improvement, secondary materials, pilot-industrial testing.*

Феррохромды құю шөміштерінің қызмет ету мерзімін қорғаушы отқа төзімді қаптамаларды қолдану арқылы ұзарту

Аңдатпа. Құю шөміштерінің қаптамаларының тозуы жоғары көміртекті феррохром өндірісіндегі негізгі мәселелердің бірі болып табылады, бұл жабдықтың қызмет ету мерзімінің қысқаруына және шығындардың артуына әкеледі. Жұмыста ***FeCr*** 800–850 феррохромын құю кезінде қорғаныш отқа төзімді қаптамалардың тиімділігі зертханалық және тәжірибелік-өнеркәсіптік деңгейде бағаланды. Шамот, кварцит және қайталама материалдар негізіндегі әртүрлі байланыстырғыштары бар жабындар зерттелді. Сұйық шынының адгезиясы төмен екені анықталды, ал цемент – бентонит – органикалық қоспа негізіндегі кешенді байланыстырғыш ең жоғары тұрақтылықты көрсетті. Шамотты қаптамалар шөміштің қызмет ету мерзімін 13–18 балқытуға дейін арттырады (базалық режимдегі 10 балқытуға қарсы), кварцитті қаптамалар орташа әсер береді, ал қож негізіндегі қаптамалар тиімсіз болып табылады.

Түйінді сөздер: *жоғары көміртекті феррохром, құю шөміші, отқа төзімді қаптама, қызмет ету мерзімін арттыру, екінші реттік шикізат, тәжірибелік-өнеркәсіптік сынақтар.*

Повышение срока службы разливочных ковшей для феррохрома с использованием защитных огнеупорных покрытий

Аннотация. Износ футеровки разливочных ковшей является ключевой проблемой производства высокоуглеродистого феррохрома, приводящей к снижению срока службы и росту затрат. В работе выполнена лабораторная и опытно-промышленная оценка защитных огнеупорных покрытий при разливке феррохрома ***FeCr*** 800–850. Исследованы покрытия на основе шамота, кварцита и вторичных материалов с различными связующими. Установлено, что жидкое стекло обеспечивает низкую адгезию, тогда как комбинированное связующее (цемент – бентонит – органическая добавка) демонстрирует наилучшую стабильность. Шамотные покрытия увеличивают срок службы ковша до 13–18 плавок (против 10 в базовом режиме), кварцитовые обеспечивают умеренный эффект, а шлаковые покрытия являются неэффективными.

Ключевые слова: *высокоуглеродистый феррохром, разливочный ковш, огнеупорная футеровка, увеличение срока службы, вторичное сырье, опытно-промышленные испытания.*

Introduction

Degradation and wear of refractory linings exposed to metal–slag melts remain a significant technological issue in modern metallurgical processes. Premature damage of ladle linings and casting equipment can result in unexpected production interruptions, higher maintenance expenditures, and a decline in operational reliability and safety [1–3]. Consequently, improving the durability of refractory materials has become an important objective in the context of increasing demands for energy efficiency and cost optimization.

The production of high-carbon ferrochrome is associated with elevated melt temperatures, chemically aggressive metal-slag systems, and severe thermomechanical stresses acting on refractory materials. Interaction between ferrochrome slags and refractory linings involves processes such as chemical dissolution, slag infiltration, and thermochemical corrosion, all of which contribute to accelerated lining wear and reduced service life [4–6]. Additional deterioration occurs during the mechanical removal of metal–slag accretions, which damages the lining surface and intensifies wear processes [7].

Conventional methods for extending ladle lining lifetime include increasing the thickness of refractory masonry or applying monolithic refractory materials. However, a thicker lining decreases the effective ladle capacity and increases the overall weight of the structure, which negatively affects technological performance and increases the load on lifting equipment.

An alternative approach involves the application of protective refractory coatings to the working surface of ladle linings. Such coatings, typically composed of finely dispersed refractory materials combined with inorganic binders, can reduce both chemical and mechanical interaction with the primary lining, as reported in several review and industrial studies [8]. This approach is widely applied in steelmaking, where the effectiveness of protective coatings for ladles and intermediate vessels has been confirmed in both laboratory and industrial conditions [9].

Recently, increasing attention has been given to the use of secondary refractory and metallurgical materials, such as ferroalloy slags and industrial dusts, in coating compositions. Their use corresponds to resource-efficiency and circular economy principles but requires experimental verification of thermal stability, chemical compatibility, and resistance to aggressive metal-slag melts [10]. For high-carbon ferrochrome production, systematic studies in this area remain limited.

In this context, the present study provides a comparative laboratory evaluation of several protective refractory coating compositions, followed by pilot-industrial validation under ferrochrome casting conditions. Unlike steelmaking processes, ferrochrome production is characterized by higher temperatures and increased chemical aggressiveness of chromium-containing slags, which intensifies refractory wear and necessitates adaptation of protective coatings to ferroalloy conditions.

The novelty of the work lies in the systematic laboratory and pilot-industrial assessment of coatings based on both primary and secondary refractory materials, including ferrochrome slags and industrial dusts, as well as in the application of a combined binder system providing enhanced adhesion and thermal stability.

Methods

Industrial Context and Description of Casting Ladles

The production of high-carbon ferrochrome at the Aktobe Ferroalloy Plant is carried out under conditions of high metal-slag temperatures and increased chemical aggressiveness toward refractory materials. Ferrochrome smelting is performed in two production units: Smelting Shop No. 4 and Smelting Shop No. 1, equipped with direct-current and alternating-current electric arc furnaces, respectively.

The main volume of ferrochrome is produced in Smelting Shop No. 4, where casting is performed without intermediate equipment. The remaining production is smelted in Smelting Shop No. 1, where the casting process involves the use of dedicated casting ladles.

Although identical grades of high-carbon ferrochrome are produced in both shops, the casting conditions and auxiliary equipment differ, which affects the operating conditions of refractory linings. In Smelting Shop No. 1, casting ladles are a key element of the technological process and are subjected to intense thermochemical and mechanical loads.

The casting ladle is a steel structure with a flat bottom, equipped with side trunnions for transportation and tilting (Figure 1). Its inner surface is lined with chamotte refractory bricks of grade ShB-5.

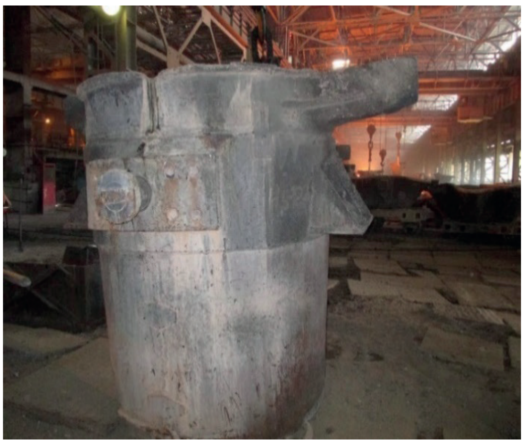

Figure 1. General view of the casting ladle used in Smelting Shop No. 1.
Сурет 1. № 1 Балқыту цехында қолданылатын құю ожауының жалпы көрінісі.
Рис. 1. Общий вид разливочного ковша, используемого в плавильном цехе № 1.

The lining of casting ladles is constructed in one or two layers depending on the grade of the cast ferrochrome and its chemical composition. During the casting of ferrochrome grades ***FeCr*** 800–950 with a carbon content of 8.01–9.49 wt. %, a single-layer lining is applied, in which chamotte bricks are installed on edge with a radial orientation relative to the vertical axis of the ladle. The average service life of such a lining reaches up to ten heats.

When casting ferrochrome grades ***FeCr*** 600–650 with a reduced carbon content (6.01–6.49 wt. %), a two-layer lining configuration is used, in which the bricks are laid flat (Figure 2). This configuration facilitates replacement of the working lining layer; however, its service life typically does not exceed six heats, which is attributed to the increased chemical aggressiveness of the melt toward chamotte refractory materials.

Thus, the operating conditions of casting ladles in Smelting Shop No. 1 are characterized by intense thermochemical interaction between the metal-slag melt and the refractory lining, as well as additional mechanical loads during the removal of metal-slag accretions after casting. Therefore, the limited service life of the lining, even with a two-layer configuration, requires additional protection methods, including the application of protective refractory coatings to the working surface.

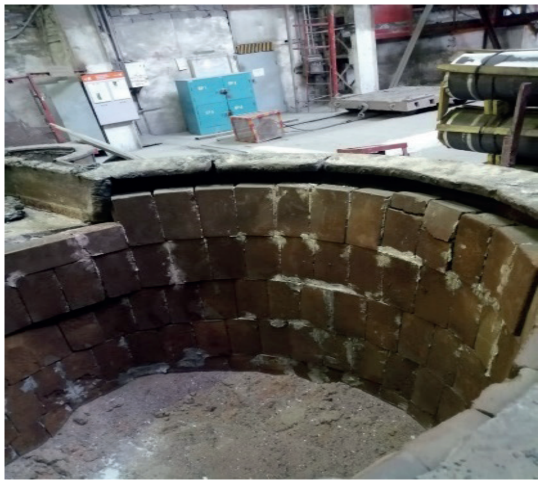

Figure 2. Lining of the ladle for casting ferrochrome grades FeCr 600–650.
Сурет 2. FeCr 600–650 маркалы феррохромды құюға арналған ожаудың қаптамасы.
Рис. 2. Футеровка ковша для разливки феррохрома марки FeCr 600–650.

Materials for Protective Refractory Coatings

Protective refractory coatings intended for application to the working surface of casting ladle linings were studied. The selection of coating components was based on their refractory properties, thermal resistance, and suitability for use under high-carbon ferrochrome casting conditions.

Both primary refractory materials and secondary metallurgical raw materials from ferrochrome production were used as fillers. Primary materials included ground chamotte, microsilica, quartzite, and corundum, while secondary materials consisted of processed ferrochrome slags and industrial dust generated in plant units.

To ensure coating formation and adhesion to the refractory substrate, inorganic binders and plasticizing additives were used. Sodium silicate and sodium aluminate were used as binding agents, while bentonite clay was incorporated in several compositions to enhance mixture plasticity and improve structural stability of the coating layer.

The coating formulations were designed with consideration of their applicability under industrial ladle operating conditions and their ability to retain structural integrity during thermal loading and contact with metal-slag melts. The investigated compositions together with their approximate refractoriness values obtained in laboratory experiments are summarized in Table 1.

Sample Preparation and Thermal Treatment

Protective refractory coatings were prepared under laboratory conditions using a standardized procedure. Dry components were weighed in the required proportions and mixed in a laboratory mixer until a homogeneous mixture was obtained. The binder was then gradually added under continuous stirring to form a plastic mass. For mixtures with low wettability, plasticizers such as refractory or bentonite clay were introduced. When bentonite acted as the binder, water was added after dry mixing until the required consistency was achieved.

Table 1

Compositions of protective refractory coatings and their refractoriness

Кесте 1

Қорғаныш отқа төзімді жабындардың құрамы және олардың отқа төзімділігі

Таблица 1

Составы защитных огнеупорных покрытий и их огнеупорность

Mixture composition	Refractoriness*, °C	Remarks
Ground chamotte – 85% Bentonite (refractory clay) – 8–10% Sodium silicate – 10–20%	1730	Bentonite used as a plasticizer
Microsilica – 75% Ferrochrome slag – 5% Sodium silicate – 20%	1750	-
Quartzite Sodium silicate – 20%	1750	-
High-carbon ferrochrome slag – 80% Sodium silicate – 20%	1730	-
Baghouse dust – 90% Bentonite – 5% Sodium silicate (as required)	1890	Bentonite used as a plasticizer
Ground corundum from launders Sodium silicate / sodium aluminate	1800	-

**the refractoriness of the listed mixtures was determined by laboratory testing*

The prepared mixtures were applied to refractory substrates or molded into specimens and dried in an oven at temperatures up to 200 °C for 15 min to remove excess moisture. After cooling, the samples were visually inspected for cracks, deformation, or binder degradation.

To evaluate high-temperature behavior, the specimens were heated in a muffle furnace at 1000 °C for 15 min, followed by air cooling. The selected temperature corresponds to the onset of intensive thermochemical interaction between refractory materials and ferrochrome slags and allows evaluation of coating stability under conditions close to industrial practice. The holding time represents short-term thermal exposure typical of casting operations and is used for rapid comparative assessment of thermal stability, structural integrity, and adhesion without reproducing the full operating cycle of the ladle.

After heating, the samples were re-examined for dimensional changes and coating shrinkage. Only compositions that retained structural integrity without visible defects were selected for further testing with metal-slag melts.

Tests on Interaction with Metal-Slag Melts

The resistance of protective refractory coatings to metal-slag melts was investigated using previously prepared specimens that had undergone thermal treatment and showed no visible defects. The experiments were carried out under laboratory conditions in a Tammann furnace. High-carbon ferrochrome or the corresponding slag was melted in a refractory crucible until a stable liquid phase was obtained. After that, samples with the applied coatings on chamotte brick fragments were immersed into the melt. The exposure time was 30 min, simulating the direct interaction between the protective lining layer and liquid metal-slag melts during casting operations. After the test period, the specimens were removed and allowed to cool in air.

Following cooling, the interaction between the coatings and the melts was analyzed. The evaluation included visual assessment of wetting behavior and adhesion of metal or slag to the coating surface, as well as determination of the melt penetration depth into the protective layer. The obtained results were used to compare the resistance of the investigated compositions and to identify the most promising coatings for further pilot-industrial testing.

Criteria for Evaluating the Effectiveness of Protective Coatings

The performance of protective refractory coatings was assessed using a set of qualitative indicators describing their behavior during thermal treatment and interaction with metal-slag melts. The evaluation relied on the results obtained from laboratory experiments.

The key assessment parameters included the ability of the coating to maintain structural integrity after heating and cooling without through-thickness damage, the absence of pronounced cracking, delamination, or degradation, and the nature of the interaction between the coating and the metal–slag melt under direct contact conditions. Additional factors considered were the visually observed wetting and adhesion of the melt, the degree of melt penetration into the coating structure, and the technological suitability of the compositions, including ease of preparation and application. Coating compositions that met these requirements were regarded as the most promising candidates for further investigation and subsequent pilot-industrial testing under ferroalloy production conditions.

Pilot-Industrial Trials of Casting Ladles

Pilot-industrial testing of protective refractory coatings was performed during the production of high-carbon ferrochrome grades ***FeCr*** 800–850 at Smelting Shop No. 1. using a casting ladle with the worn refractory lining completely removed.

After installation of a chamotte brick lining according to technological regulations, protective coatings were applied to separate areas of the lining surface. The mixtures were based on ground chamotte scrap, quartzite, and ground high-carbon ferrochrome slag, using sodium silicate as the binder. During transportation of the ladle to the drying station, all coatings delaminated from the lining surface. Increasing the binder content did not improve adhesion; therefore, further trials with sodium silicate binders were discontinued.

A combined binder system consisting of cement, bentonite, and lignosulfonate (Ligno) was subsequently applied, providing stable adhesion regardless of filler type. At the first stage, the ladle was coated with a mixture containing ground chamotte (85%), cement (6%), Ligno (3%), and bentonite (6%) with a moisture content of about 20%. The appearance of the ladle with the chamotte-based protective coating before pilot-industrial operation is shown in Figure 3.

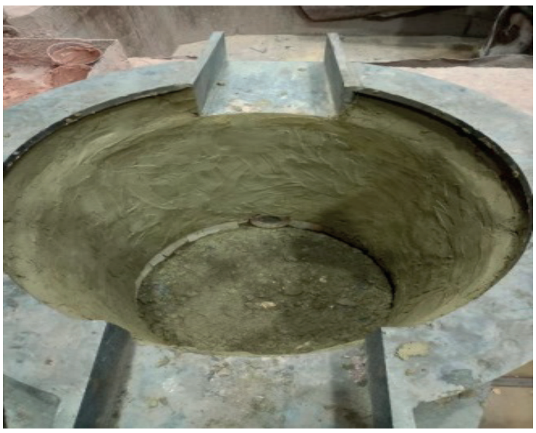

Figure 3. Appearance of the casting ladle with a chamotte-based protective refractory coating prior to pilot-industrial operation.
Сурет 3. Тәжірибелік-өнеркәсіптік пайдалану алдында шамот негізіндегі қорғаныш отқа төзімді жабыны бар құю ожауының сыртқы көрінісі.
Рис. 3. Внешний вид разливочного ковша с защитным огнеупорным покрытием на основе шамота перед опытно-промышленной эксплуатацией.

After application of the coating, the ladle was filled with sand and placed at the drying station for 30–40 min in accordance with standard operating procedures. Visual inspection showed no cracking or delamination of the protective layer, after which the ladle was put into operation without changes to the standard casting practice. Similar trials were performed for coatings based on ground quartzite and ground high-carbon ferrochrome slag using the same combined binder system. Three ladles were tested for each coating type. During operation, the number of heats until ladle withdrawal from service was recorded, and the average service life values are presented in Table 2.

A significant influence on the performance of protective coatings is exerted by the binder composition. The combined system based on cement, bentonite, and lignosulfonate provides a synergistic effect through the formation of a rigid framework, improved plasticity and adhesion, and reduced cracking.

In contrast, sodium silicate-based binders exhibit insufficient adhesion and a tendency to crack, leading to coating delamination. Thus, not only the filler composition but also the binder type plays a decisive role.

Results and Discussion

Results of Laboratory Testing of Protective Refractory Coatings

A comparative laboratory study was performed for six compositions of protective refractory coatings differing in filler materials and binder systems. The preliminary screening considered mixture plasticity, adhesion to the chamotte substrate, resistance to drying at 200 °C, and thermal stability at 1000 °C.

Several compositions demonstrated unsatisfactory characteristics. The corundum-based mixture showed insufficient plasticity and weak adhesion to the refractory substrate. Coatings containing microsilica required a higher water addition (up to about 40 wt. % of the filler), which resulted in reduced adhesion and delamination after drying. Mixtures incorporating chromite dust exhibited good plasticity and adhesion but lacked thermal stability, as drying at 200 °C caused deep cracking and partial separation of the coating layer.

The best performance was observed for coatings based on ground chamotte, quartzite, and high-carbon ferrochrome slag. These compositions maintained structural integrity after drying and subsequent heating to 1000 °C, showed no significant cracking, and adhered satisfactorily to the chamotte substrate. Consequently, these mixtures were selected for further investigation of their interaction with metal-slag melts.

Interaction of Protective Coatings with Metal-Slag Melts

Tests of metal-slag resistance revealed differences in the interaction of coatings with molten high-carbon ferrochrome, including wetting, infiltration, and adhesion layer formation.

Chamotte-based coatings showed the lowest melt infiltration and weak adhesion, indicating good chemical compatibility and thermal stability. Quartzite-based coatings exhibited moderate wetting and infiltration without significant penetration, whereas coatings based on high-carbon ferrochrome slag showed increased wetting and infiltration due to chemical affinity with the melt.

These results indicate that coating performance is governed by wettability and chemical compatibility with slag: aluminosilicate compositions provide higher resistance to melt penetration, while slag-based coatings are less effective. Thus, despite the advantages of secondary materials, their use under ferrochrome casting conditions is limited by thermochemical compatibility.

Results of Pilot-Industrial Trials of Casting Ladles

Pilot-industrial evaluation of protective refractory coatings was conducted during the production of high-carbon ferrochrome (***FeCr*** 800–850) in Smelting Shop No. 1. Ladle durability was assessed by the number of heats until withdrawal from service, with uncoated ladles used as a reference.

The results showed a clear influence of coating composition on service life. Chamotte-based coatings demonstrated the highest performance, increasing ladle lifetime to about 15 heats compared to 10 in the baseline regime. Quartzite-based coatings provided moderate improvement (11 heats), while coatings based on high-carbon ferrochrome slag were ineffective, reducing ladle life to 8 heats. The results are summarized in Table 2.

Table 2

Results of pilot-industrial trials of protective refractory coatings during FeCr 800–850 production in Smelting Shop No. 1

Кесте 2

№ 1 балқыту цехында FeCr 800–850 өндіру кезінде қорғаныш отқа төзімді қаптамаларды тәжірибелік-өнеркәсіптік сынақтан өткізу нәтижелері

Таблица 2

Результаты опытно-промышленных испытаний защитных огнеупорных покрытий при производстве FeCr 800–850 в плавильном цехе № 1

Coating type	Number of heats
No coating (baseline)	10
Chamotte-based coating	15
Quartzite-based coating	11
High-carbon ferrochrome slag-based coating	8

It should be noted that the number of pilot-industrial trials was limited (n = 3) due to production constraints; therefore, the obtained results should be considered as preliminary industrial validation. At the same time, the observed differences in ladle service life are pronounced and reproducible, confirming the influence of coating composition, although further studies with a larger number of trials are required for a more comprehensive statistical assessment.

Conclusions

A combined laboratory and pilot-industrial investigation of protective refractory coatings was carried out under conditions close to industrial operation of casting ladles in high-carbon ferrochrome production (***FeCr*** 800–850).

The results show that coating performance is governed not only by refractoriness, but also by adhesion, thermal stability, and resistance to metal–slag interaction. Chamotte-based coatings with a combined binder system (cement – bentonite – organic additive) demonstrated the highest efficiency, increasing ladle service life to 13–18 heats compared to 10 in the baseline regime.

Quartzite-based coatings provided only moderate improvement, while coatings based on high-carbon ferrochrome slag were ineffective. The results also highlight the decisive role of the binder system: sodium silicate led to coating delamination, whereas the combined binder ensured stable adhesion.

Overall, protective coatings represent an effective and economically viable method for extending ladle service life without modifying ladle design. The observed increase in durability (by approximately 30–80%) reduces maintenance frequency and associated costs, while requiring no additional capital investment.

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