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Обзорная статья

Waste reduction and implementation of environmentally safe and efficient production processes using high-silicon alloys of the Al – Si system

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Abstract. The modern metallurgical industry, especially in the field of ferrous metallurgy, faces significant challenges in improving energy efficiency, reducing waste volumes, and minimizing environmental impact. One of the promising directions is the use of high-silicon silumin alloys, which, due to their high strength, wear resistance, and thermal stability, are finding increasingly broad applications, including their capability for multiple recycling. This paper analyzes the composition and physico-mechanical properties of these alloys and their role in technological processes of ferrous metallurgy, such as smelting, casting, heat treatment, and mechanical processing. Innovative approaches aimed at reducing the energy intensity of production operations, minimizing waste, and creating closed production cycles are examined, which is particularly relevant for ferrous metallurgy, where waste volumes are traditionally high. Examples of application of high-silicon silumins in the production of casting molds, wear-resistant coatings, and structural materials for heavy industries are provided. Special attention is given to recycling and waste utilization technologies at metallurgical enterprises, contributing to lower production costs and increased competitiveness. Thus, the use of high-silicon silumin alloys demonstrates potential for shaping environmentally friendly, energy-efficient, and economically sustainable processes in ferrous metallurgy.

Keywords: high-silicon silumin alloys, energy efficiency, sustainable development, waste minimization, closed production cycle, material recycling, wear resistance, heat treatment, reduction of energy intensity

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Уменьшение количества отходов и внедрение экологически безопасных и эффективных производственных процессов при использовании высококремнистых сплавов системы Al – Si

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Аннотация. Современная металлургическая промышленность, особенно в области черной металлургии, сталкивается с важными задачами повышения энергоэффективности, сокращения объемов отходов и минимизации негативного воздействия на окружающую среду. Одним из перспективных направлений является применение высококремнистых силуминовых сплавов, которые благодаря своей высокой прочности, износостойкости и термической стабильности находят все более широкое применение, включая возможность их многократной переработки. В настоящей работе авторы анализируют состав и физико-механические свойства этих сплавов, их роль в технологических процессах, таких как плавка, литье, термическая и механическая обработки. Особенно актуальными для черной металлургии, где объемы отходов традиционно высоки, являются рассмотренные инновационные подходы, которые направлены на снижение энергоемкости производственных операций, минимизацию количества отходов и создание замкнутых циклов производства. Приведенные примеры демонстрируют возможности применения высококремнистых силуминов в производстве литейных форм, износостойких покрытий и конструкционных материалов для тяжелой промышленности. Особое внимание уделено технологиям переработки и утилизации отходов на металлургических предприятиях, что способствует снижению себестоимости продукции и повышению конкурентоспособности. Таким образом, применение высококремнистых силуминовых сплавов демонстрирует потенциал для формирования экологически безопасных, энергоэффективных и экономически устойчивых процессов в черной металлургии.

Ключевые слова: высококремнистые силуминовые сплавы, энергоэффективность, устойчивое развитие, минимизация отходов, замкнутый производственный цикл, переработка материалов, износостойкость, термическая обработка, снижение энергоемкости

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Introduction

The modern metallurgical industry faces challenges associated with the need to improve energy efficiency, reduce waste generation, and decrease environmental impact. In this context, special attention is given to materials capable of significantly enhancing technological processes and contributing to the development of closed production cycles. One promising group of such materials is high-silicon silumin alloys, which are notable not only for their high strength and wear resistance but also for their recyclability – an attribute consistent with the principles of sustainable development [1].

The aim of this study is to examine the findings of recent research on the application of high-silicon silumin alloys, their technological integration into production processes, and their impact on environmental safety at all stages of manufacturing.

Characteristics of high-silicon silumin alloys

Composition and structure

According to the state diagram (Fig. 1), eutectic, hypoeutectic, and hypereutectic compositions can coexist in equilibrium. Each of these is associated with different alloy preparation modes. Alloys containing more than 13 % Si and consisting of primary silicon crystals, intermetallic compounds, and eutectic are classified as hypereutectic [2]. These alloys typically exhibit a coarse acicular structure composed of eutectic (α-Si) and primary silicon crystals.

In such alloys, silicon acts as an alloying element that promotes the formation of a fine-dispersed structure and enhances the material's hardness and wear resistance. Increased silicon content improves thermal stability, which is essential for processing and the subsequent use of products [3]. Several studies note that the optimal ratio of silicon to other alloying elements (e.g., copper, magnesium) enables a balance between mechanical properties and material machinability [4].

Physico-mechanical properties

Studies have shown that high-silicon silumins possess high strength, corrosion resistance, and wear resistance [5]. Their enhanced thermal stability helps to counteract the effects of thermal aging and reduces the likelihood of crack formation under dynamic loads [6]. Microstructural analysis of these alloys reveals the presence of fine-dispersed phases, making them ideal for use under high-temperature conditions and in aggressive environments [7]. It is important to note that test results confirm the feasibility of using such alloys in both the aerospace and automotive industries, where high mechanical loads must be withstood while minimizing the weight of the component [8; 9].

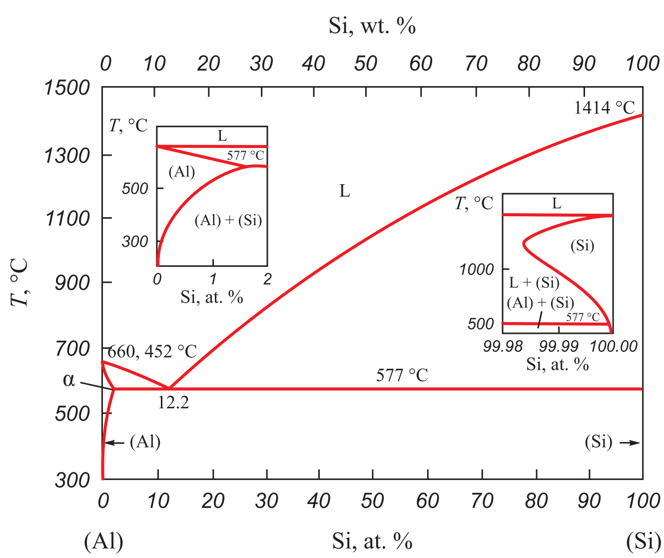

Fig. 1. Al – Si state diagram [2]

Рис. 1. Диаграмма состояния Al – Si [2]

Technological aspects of integration into production processes

Initial metal preparation

The initial stage of integrating high-silicon silumin alloys into production involves raw material preparation. Modern melting techniques employing induction furnaces and electric furnaces with controlled atmospheres facilitate the production of alloys with low impurity content and high structural homogeneity [10]. Automated systems for analyzing the chemical composition of melts enable optimization of the technological process and ensure compliance with the specifications of the final product.

Casting and molding technologies

The use of innovative die casting technologies enables high-precision molding and minimizes process-related losses. When developing optimal casting modes, researchers pay particular attention to controlling melt temperature and cooling rate [11]. Rapid cooling promotes the formation of a fine-dispersed microstructure, which is critical for achieving superior mechanical properties in silumin alloys. Studies [12; 13] have demonstrated that the application of pulsed cooling technologies reduces internal stresses in the material, thereby enhancing the performance characteristics of the final products.

Heat treatment and deformation

After molding, high-silicon silumin alloys undergo comprehensive heat treatment, including annealing, normalizing, and quenching under various modes. The purpose of these processes is to achieve an optimal balance between the strength and ductility of the material [14]. Several studies note that pulsed heat treatment contributes to improved structural homogeneity and also reduces the energy intensity of the processes, which is particularly relevant in the context of sustainable development [15].

Mechanical processing and quality control

Modern mechanical processing technologies – including rolling, stamping, and milling – are integrated into the overall production workflow to achieve the required product geometry and minimize defects. The use of automated quality control lines, supplemented by artificial intelligence systems, allows real-time monitoring of processing parameters and prompt adjustment of technological modes [16]. This not only improves the quality of the final products but also reduces material losses.

Environmental safety and sustainable development principles

Reducing the energy intensity of production

One of the key aspects in the development of sustainable production processes is the reduction of the energy intensity of technological operations. Studies confirm that the use of high-silicon Al–Si alloys helps to reduce the energy intensity of such operations due to their high thermal stability and improved machinability. In particular, optimization of heat treatment parameters for these alloys results in shorter processing times without compromising mechanical properties. For example, in [17], it is reported that due to the high solidification rate and fine microstructure (Fig. 2), the duration of solidus treatment can be reduced by up to 50 % while maintaining high strength characteristics: a tensile strength of 330 MPa and a yield strength of 300 MPa.

Additionally, the study [18] shows that optimizing process parameters – such as energy density – results in a denser, more homogeneous microstructure in the Al – 42Si alloy, enhancing its mechanical properties and reducing the need for additional processing. Consequently, the use of silumin alloys helps lower greenhouse gas emissions and reduces the overall environmental footprint of production.

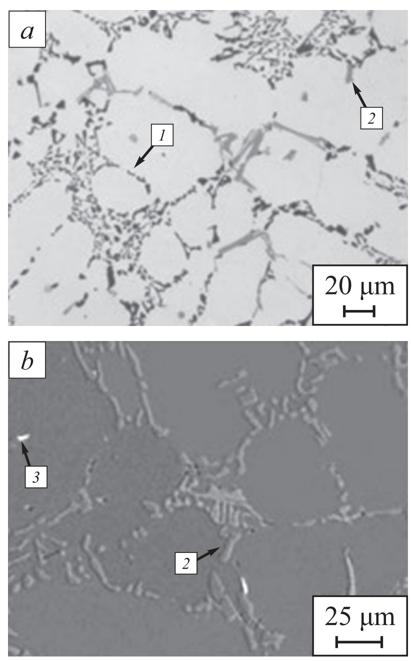

Fig. 2. Finished alloy microstructure (SDAS = 25 μm) (Al–Si (*1*) eutectic and Al–Si–Mg–Cu (*2*) phase)

Рис. 2. Микроструктура сплава в готовом виде (SDAS = 25 мкм) (эвтектика Al–Si (*1*) и фаза Al–Si–Mg–Cu (*2*))

Minimization of waste and organization of a closed production cycle

In line with the principles of sustainable development, a key focus is the creation of closed production cycles, where waste is recycled and reintegrated into the technological process. High-silicon silumin alloys are well suited for secondary processing. Studies [19; 20] explore technologies for recycling graded scrap without compromising the original material properties, thereby reducing the overall volume of technological waste. The application of ultra-clean recycling methods and waste deoxidation enables the establishment of a fully closed production cycle, thereby minimizing environmental impact.

Environmentally sound operation and extended service life

Durability and exceptional resistance to corrosion are among the key advantages of high-silicon silumin alloys. Over the long term, this translates into fewer repairs and replacements for products made from these materials, resulting in reduced raw material consumption and lower maintenance costs. Operational studies [21; 22] confirm that structures manufactured from these alloys exhibit significantly greater durability compared to conventional materials, thereby supporting resource conservation and minimizing environmental impact.

Technological innovations and practical applications

Application in the automotive industry

One of the key sectors where high-silicon silumin alloys are widely used is the automotive industry. Their light weight, high strength, and corrosion resistance make these materials attractive for manufacturing body components, engine blocks, and other structural parts [23]. Studies [24] show that reducing a vehicle's weight by 10 % can lead to a 6 – 8 % decrease in fuel consumption, which corresponds to a reduction in CO_2 emissions of 8 – 11 g/km.

Application in the aerospace industry

High-silicon silumin alloys are indeed used in the aerospace industry due to their high specific strength and low density, which allow for structural weight reduction without compromising mechanical performance. However, their application is primarily limited to components that do not bear significant loads, such as electronic packaging materials and engine accessories [25].

Fig. 3 illustrates possible applications of cast aluminum alloys in the aerospace sector – for instance, investment casting of a forward access door, precision casting of a baggage compartment door and flap guide rails from aluminum alloy, and high-quality castings used in aircraft interiors. In this industry, aluminum casting alloys typically contain silicon (Si), copper (Cu), and magnesium (Mg).

Industrial production and waste utilization

One of the latest trends in the modern metallurgical sector is the development of integrated waste recycling systems. Studies [27; 28] highlight examples involving high-silicon silumin alloys, in which graded production scrap is recycled while preserving its original composition and structure. These systems not only make recycling economically viable but also significantly reduce the cost of producing primary materials. When combined with advanced quality control technologies, secondary processing becomes an essential element of a sustainable production cycle.

Environmental and economic benefits of silumin alloy integration

Economic efficiency

The comprehensive integration of high-silicon silumin alloys into production processes offers a range of eco-

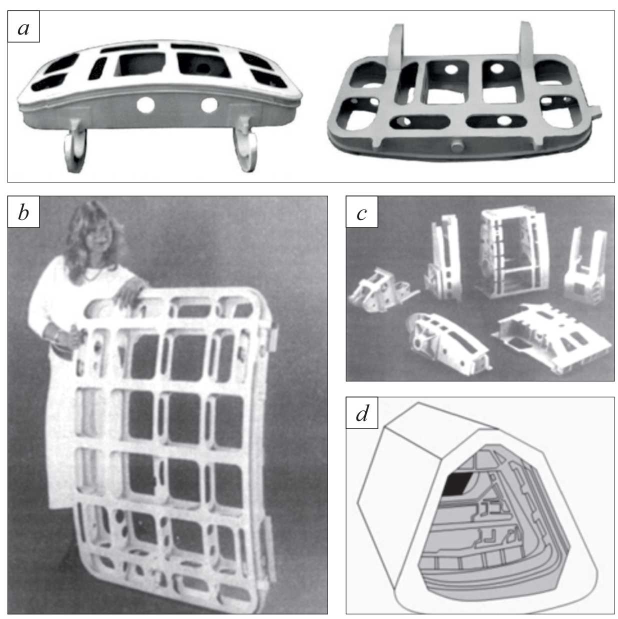

Fig. 3. Castings for aerospace applications:
a – casting using FAD technology for Boeing 737 [26]; *b* – *c* – precise casting of luggage compartment door guides; *d* – interior casting

Рис. 3. Отливки для аэрокосмического применения:
a – литье по технологии FAD для Boeing 737 [26]; *b* – *c* – точное литье направляющих дверей багажного отделения; *d* – литье салона

nomic benefits. Reduced energy intensity of technological operations, lower process-related losses, and the possibility of secondary waste recycling contribute to the optimization of production costs [29]. Companies implementing such technologies report a decrease in the cost of finished products, allowing them to remain competitive in the global market. In addition, lower maintenance expenses and increased product durability further enhance the overall economic efficiency of productio [30].

Environmental safety

Sustainable development is impossible without consideration of environmental and economic factors. High-silicon silumin alloys, owing to their numerous advantageous properties, contribute to reducing the environmental impact of industrial production. Lower emissions of harmful substances, minimized generation of process waste, and the potential for subsequent recycling align with global trends in environmentally conscious manufacturing. In particular, studies show that recycling silicon waste by alloying it with aluminum enables the efficient utilization of production residues, thereby reducing waste volumes and lessening environmental impact. A study focused on the closed cycle of composite material recycling provides detailed examples of the successful implementation of such technologies, highlighting the strong potential of modern manufacturing in the context of sustainable development. The authors examine a solid-state recycling route involving crushing and sintering, which preserves the material's properties and reduces the need for primary resources [31].

Prospects for further research

Composition modification and alloying

Further research on Al–Si aluminum alloys with silicon content above 15 % focuses on identifying optimal alloying additives. Recent experimental studies aim to modify the composition in a way that enhances not only the mechanical but also the environmental properties of the material. In particular, the addition of copper and magnesium promotes the formation of secondary phases, which improves the strength characteristics of the alloy. However, it should be noted that increasing copper content may have a negative effect on the alloy's environmental performance. Therefore, it is essential to carefully control the ratio of alloying elements to achieve an optimal balance between mechanical and environmental properties [32].

Advancement of technological methods

The development and implementation of innovative methods for monitoring microstructural changes during heat and mechanical treatment of high-silicon silumin alloys represent promising research directions. The use of digital technologies, physical process modeling, and artificial intelligence (AI) enables real-time optimization of production parameters, improving the efficiency of integrating these alloys into manufacturing processes.

Studies show that the application of AI in aluminum alloy development can significantly accelerate the creation of new materials. With AI, it is possible to predict the properties of potential alloys before physical testing, reducing development time by up to 50 % and cutting costs by 40 %[1].

In addition, AI is used to optimize parameters in the additive manufacturing of aluminum alloys. A systematic review highlights AI applications for real-time monitoring in laser-based additive manufacturing processes, contributing to improved product quality and production efficiency [33].

Thus, the integration of digital technologies and artificial intelligence into the processing of high-silicon silumin alloys improves the monitoring of microstructural changes and the optimization of production parameters, thereby enhancing overall efficiency and product quality.

Environmental assessment and standardization

Let us examine the key stages of aluminum production from the perspective of atmospheric emissions – beginning with the mining of bauxite and nepheline ores, followed by raw material processing into alumina, the production of anodes and anode paste, primary aluminum smelting, and casting operations (Fig. 4).

Bauxite and nepheline are typically extracted using open-pit mining methods, which result in significant emissions of various pollutants into the atmosphere, including mechanical dust, carbon monoxide (CO), hydrogen sulfide, and nitrogen oxide (NO). These substances eventually settle into the soil and contaminate water resources. Addressing these issues requires not only technological improvements in production processes, but also the development of regulatory frameworks to ensure environmental safety. Comprehensive environmental assessments are planned to establish standards for waste recycling and disposal, along with practical recommendations for enterprises aimed at reducing their carbon footprint [35]. Such research plays a vital role in shaping national policy on environmental protection and sustainable development.

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The integration of high-silicon silumin alloys into manufacturing processes represents a timely and forward-looking approach that supports the principles of sustainable development and environmental responsibility. The use of these materials allows for the optimization of production stages – from initial metal preparation to waste utilization and secondary recycling – creating new opportunities for resource conservation, lower energy consumption, and reduced environmental impact.

Recent studies confirm that high-silicon silumin alloys exhibit unique physical and mechanical properties, making them well suited for use across a wide range of industries, including automotive, aerospace, and other high-tech sectors. Advances in melting, casting, and both thermal and mechanical processing enable the production of materials with a high degree of structural uniformity, minimal process-related losses, and excellent overall quality [36]. A well-structured secondary recycling system further enables the development of fully closed production cycles – an essential step toward achieving sustainable industrial growth.

The benefits of using high-silicon silumin alloys extend beyond improvements in product quality – they also enhance the economic efficiency of manufacturing. Lower energy consumption, reduced waste generation, and longer product service life all contribute to the increased global competitiveness of the domestic metallurgical industry [37]. As such, the implementation of innovative technologies based on these alloys provides a strong foundation for the continued advancement of manufacturing with minimal environmental impact.

Despite the progress already achieved, further research remains highly relevant. Strengthening scientific and technological collaboration, advancing digital technologies for process monitoring and modeling, and improving waste recycling methods represent promising directions for future developments [38]. Government support and international cooperation in this area may become key drivers for the implementation of innovations in production processes, leading to a reduced environmental footprint for the metallurgical sector and supporting the sustainable development of the economy.

Conclusions

The integration of high-silicon silumin alloys presents a promising opportunity for the creation of environmentally friendly and economically efficient manufacturing processes. The adoption of these technologies aligns with current sustainable development goals and constitutes a meaningful contribution to addressing global environmental challenges. Future research prospects offer opportunities to expand the range of applications of high-silicon silumins, enhance their properties, and optimize technological processes – paving the way for a modern, clean, and energy-efficient metallurgical industry.

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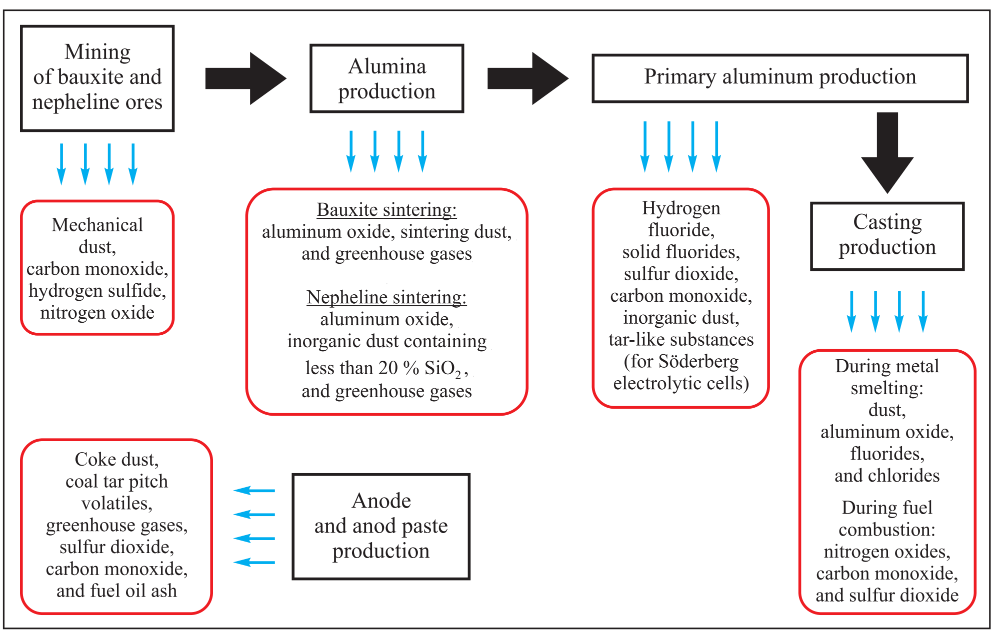

Fig. 4. Stages of aluminum production and emissions into the atmosphere [34]

Рис. 4. Этапы производства алюминия и выбросы в атмосферу [34]

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