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APPROACHES IN METALLURGY: INTEGRATION OF INNOVATION AND SUSTAINABLE DEVELOPMENT

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The modern development of the metallurgical industry is characterized by a transition from traditional technological schemes to innovative, resource-efficient, and digitally oriented approaches. Global challenges related to the growing demand for metal products, the need to reduce energy consumption, and the minimization of environmental impact are driving the active implementation of advanced technologies that shape the concept of so-called “smart” or digital metallurgy. In this context, progressive approaches encompass production digitalization, the application of mathematical modeling methods, the development of additive manufacturing technologies, as well as the implementation of sustainable development and decarbonization principles [1, 2].

One of the key directions in the transformation of metallurgy is the integration of the Industry 4.0 concept, which involves the widespread use of digital technologies, the Internet of Things (IoT), big data, and artificial intelligence. The implementation of such solutions enables the creation of cyber-physical production systems that ensure automated process control, increased flexibility, and adaptability. In particular, the use of sensor systems and data analytics allows real-time monitoring of technological parameters, optimization of resource consumption, and improvement of product quality [3, 4]. At the same time, digitalization is transforming not only production but also logistics, forming integrated value chains in which information flows play a crucial role.

A significant element of modern progressive approaches is the development of digital modeling and computational process design. The combination of classical metallurgical knowledge with advanced computational methods enables the prediction of material behavior, optimization of process parameters, and reduction in the number

of costly industrial experiments. These approaches are particularly important for extractive metallurgy, where the complexity of physicochemical processes requires accurate models to ensure process efficiency and environmental safety [5, 6]. The application of numerical methods, especially the finite element method (FEM), allows for detailed analysis of deformation processes, heat transfer, and phase transformations, forming the basis for the development of digital twins of metallurgical units.

Another important progressive direction is the advancement of additive manufacturing and powder metallurgy. Within the Industry 4.0 paradigm, additive manufacturing is considered a key enabling technology for producing complex components with tailored properties. These technologies significantly reduce material waste, shorten production cycles, and ensure high manufacturing precision. Furthermore, the integration of additive technologies with digital models opens new opportunities for product customization and microstructural optimization [7, 8].

Special attention in modern metallurgy is devoted to environmental sustainability and the development of green metallurgy. The metallurgical industry is one of the largest sources of greenhouse gas emissions, accounting for approximately 7–9% of global CO₂ emissions, making decarbonization a strategic priority [2, 9].

Progressive approaches in this area include the use of hydrogen-based iron reduction technologies, the transition to electric arc furnaces powered by renewable energy, the implementation of carbon capture and storage (CCS) technologies, and the development of circular economy principles. The latter involves the recycling and reuse of metallic waste, contributing to reduced consumption of primary raw materials and energy.

An important aspect of progressive transformation is also the integration of sustainable resource management principles. Modern metallurgical enterprises increasingly focus on improving energy efficiency, optimizing material flows, and minimizing waste generation. In this regard, digital energy management systems play a significant role, enabling the analysis and forecasting of energy consumption and facilitating the implementation of energy-saving technologies [4, 9]. Additionally, the development of circular economy concepts contributes to the emergence of new business models based on closed-loop resource utilization.

Equally important is the impact of progressive approaches on the organizational and workforce aspects of metallurgical production. The transition to digital technologies necessitates a new generation of professional engineers who possess not only metallurgical expertise but also competencies in information technologies, data analytics, and automation. This contributes to the formation of a new paradigm of professional training aligned with the requirements of the digital economy [1].

In conclusion, progressive approaches in metallurgy are shaping a new model for the development of the industry, based on the integration of digital technologies, innovative production processes, and sustainability principles. The implementation of Industry 4.0 concepts, the advancement of digital modeling, additive manufacturing, and green metallurgy ensure increased production efficiency, reduced environmental impact, and enhanced competitiveness of enterprises. In the long term, these trends will define the evolution of metallurgy as a high-tech and environmentally responsible sector playing a key role in modern industry.

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ВПЛИВ РОЗВИТКУ ІННОВАЦІЙНИХ ТЕХНОЛОГІЙ ТА КОНСТРУКЦІЙ ВДЕ НА ЕНЕРГОНЕЗАЛЕЖНІСТЬ КРАЇН

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У сукупності множин глобальних проблем: зміна клімату, катастрофічне забруднення довкілля, зменшення можливостей видобутку викопних видів палива, а також з'ясування можливостей розвитку здобування енергії в обсягах на мега-, мезо- та мікрорівнях пропозиції та активізація використання відновлювальних джерел енергії (ВДЕ) є нагальною потребою будь-якої країни світу.

Експерти з питань енергетики стверджують, що відновлювальна (альтернативна) енергетика на даний час розвитку суспільства вже придбала

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