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IMPLEMENTATION OF INDUSTRY 4.0 AND CIRCULAR ECONOMY STRATEGIES IN ALUMINUM SCRAP PROCESSING

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In today's economic and social and political conditions in Ukraine reducing import dependence and production costs, preservation of the environment, and utilization of scrap metal streams are of particular importance. The country has practically lost its own aluminum production, while aluminum is widely applied in all the industries; additionally a significant amount of aluminum scrap is expected as a result of military actions. Aluminum is a circular material that does not lose its properties during processing. One of the ways for improving the economic situation in Ukraine and transition to a circular economy is the production of aluminum alloys from secondary raw materials and products from them. Recycling requires only nearly 5 % of the energy needed to produce the primary metal, resulting in significant decrease of greenhouse gasses emissions, economy efficiency and conservation of natural resources. Circularity plays a leading role in achievement of goals of sustainable development. Production of secondary aluminum alloys is considered as a sustainable activity. However, the use of recycled aluminum alloys for the manufacturing of responsible parts, e.g. used in aviation and automotive industries, is possible with the use of effective sorting and metallurgical processing. The literature search had shown that among the most promising Industry 4.0 technologies in regard to aluminum recycling are the Internet of Things, Virtual Reality, Augmented Reality and artificial intelligence. The world's leading experience has proven the effectiveness of the use of simulated reality, in particular simulated heat treatment, which is an integral part of the aluminum alloys production technology. Machine vision and machine learning are important for sorting of metal scrap, acting its classification. A wide range of studies is dedicated to the specifics of Laser Induced Breakdown Spectroscopy applications, providing smart sorting of aluminum scrap. Some Industry 4.0 technologies are important in the context of occupational safety: digital twins can provide guidance for work performance, cobots can eliminate physical and psycho-physiological harmful and dangerous occupation effects influencing a human, etc. Circular economy (through recycling) and Industry 4.0 are promising solutions to mitigate the negative consequences of manufacturing. Potential and challenges from linking these two paradigms with secondary production, meaning adoption of Industry 4.0 in aluminum recycling, have been analyzed.

Key words: *aluminum, recycling, Industry 4.0, circular economy, sustainable development.*

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Introduction. The resource- and energy-intensive industries play a key role in the formation of Ukraine's gross domestic product (GDP) (Li et al., 2020; Ostapenko, 2021; Sotnyk, 2015). In 2021 GDP of Ukraine exceeded the GDP of European Union countries by nearly 4 times (WorldData, 2021) that indicates a quite low level of industrial development and low energy efficiency of manufacturing (Bryzhan, 2016; Khalatur et al., 2019; Koval et al., 2021; Vasylieva et al., 2021). Machines and mechanisms are often capital goods with a long life cycle of more than 20 years (Pidorycheva & Antoniuk, 2022; Slobodianiuk & Klochkovskyi, 2022; Sviezhentsev, 2016). The share of overall production in the structure of global greenhouse gasses (GHG) emissions is about 6 %; in Ukraine this indicator reached 18 % before the beginning of military actions (Petrovic et al., 2021; Yang et al., 2022). Regarding aluminum sector it contributes around 4 % of industrial CO_2 emissions (Napp et al., 2014). This necessities the development of production management (Skuibida, 2021), waste management (Andryeyeva et al., 2021; Kutsevych et al., 2020; Mashchenko et al., 2017; Morone et al., 2022), energy effective production (Mykoliuk, 2018; Smygol et al., 2021; Vasylieva et al., 2021) as key principles of state policy of Ukraine. Minimizing the negative impact on the environment by switching to circular business models (Calinescu et al., 2023; Deineko et al. 2019, Shpak et al., 2020; Sosnovska & Shtepa, 2020; Trushkina, 2022) is of particular importance.

As a result of military actions on the territory of Ukraine a lot of infrastructure objects and production facilities were already destroyed as well as a significant degradation of the environment is observed (Racioppi et al., 2022; Rawtani et al., 2022). The actions for the recovery of the economy of Ukraine include the modernization of obsolete industrial capacities on the one hand and reconstruction of destroyed ones on the other, which should be based on sustainable development and circular economy principles, Industry 4.0 and Industry 5.0 paradigms. Within the framework of the Recovery Plan of Ukraine, a list of National programs for achieving key results in economic development has been determined. The most prioritized and those that require the largest investments are measures for energy independence and Green Deal, reconstruction of a clean and protected environment, development of sectors of the economy with the added value (development of start-up ecosystems, metallurgy, programs «Engineering: increasing the innovative activity of enterprises» and «Mechanical engineering: to create a hub of automotive components for automotive clusters in Central Europe»), strengthening defense and security (in particular, the State targeted scientific and technical programs for the development of the aviation industry) (Ukraine

Recovery Plan). The necessity of energy policy transformations for sustainable implications are also of great concern (Kuzemko et al., 2022).

Ukraine has joined the global process of sustainable development in order to ensure responsible economic growth and solve ecological problems. Sustainable development goals adopted by the United Nations are reflected in the national strategic framework for Ukraine up to 2030 (United Nations Development Programme; Verkhovna Rada of Ukraine). The concept of circular economy and circular business models has become a priority toolkit for clean environment (Herrero-Lunaet al., 2022; Kara et al., 2022; Regueiro et al., 2022; Ruda & Myrka 2020). In the context of implementation of the circular economy paradigm into the state policy, the goal of sustainable development No. 12 "Responsible consumption and production" is of the greatest concern. Among the areas of cooperation between Ukraine and the European Union is the creation of production facilities for waste processing (National Institute for Strategic Studies). Recycling of aluminum corresponds to the set goal; researchers define aluminum as a perfect metal for circular economy (Graedel et al., 2019; Saevarsdottir et al., 2021; Stewart et al., 2018; Yuzer et al., 2022). What is also important, implementation of circular economy measures in the aluminum industry positively affects the ecological conditions, facilitating the Green Deal (Han et al., 2017; Haupt & Hellweg, 2019).

Aluminum is a strategic metal consumed by practically all the industries of Ukraine, including the aviation and automotive industries, mechanical engineering, defense industry, renewable energy, industrial and civil engineering. Economical demands for aluminum in Ukraine are satisfied mainly by its import. Today and in the perspective of the country's reconstruction as well, there is a need for utilization of a large amount of aluminum scrap, which additionally formed in the result of military actions in order to save currency funds.

One of the priority directions in this context is implementation of Industry 4.0 technologies taking into consideration effects and indicators specific to a definite region and economic sector (Kupalova et al., 2021). It is important to carry out an evaluation of prospects of Industry 4.0 technologies in aluminum manufacturing as well as risk assessment when introducing Industry 4.0 solutions into the recycling sector. of of possible risks when introducing Industry 4.0 technologies into the recycling of aluminum alloys in Ukraine. In modern conditions circular economy through recycling and Industry 4.0 are promising solutions to mitigate the adverse consequences of production (Blomeke et al., 2020) and can be applied to production of aluminum alloys in Ukraine.

Materials and Methods. The aim of the study is to conduct a literature survey of Industry 4.0 technologies for aluminum recycling in the framework of circular economy. The main tasks of the research is to analyze possibilities of Industry 4.0 technologies for modernization and restoration of machine-building and metallurgical industries for aluminum recycling technological operations. As research methods generalization, systematization, empirical research, systematic and logical approach were used for literature review of the theoretical basis for Industry 4.0 technologies in aluminum alloys recycling.

Results. Aluminum production presents the fastest growing metal industry (Bhattacharya, 2022; Hao et al., 2016; Saevarsdottir et al., 2020; Watari et al., 2021; Weritz & Dudek, 2022) and its demand is expected to increase from 64 mt ($ 169.8 bn) in 2021 to 80 mt ($ 277.5 bn) by 2030 (Statista; Precedence Research). For manufacturing of aluminum alloys as primary as secondary raw materials are used. About 35 % of currently produced aluminum comes from scrap and industrial waste and up to 40 % is already involved in the production chain (Bertram et al., 2017; International Aluminium Institute).

Recycling of scrap and waste permits to eliminate ecological shortcomings, decrease energy intensity and increase economic efficiency. Aluminum recycling can reduce GHG emissions by nearly 93…95 % in comparison with primary aluminum production (BIR; Hao et al., 2017; Wagiman et al., 2020). According to the estimations (Pedneault et al., 2021), total emissions of 1250…1590 Gt CO_2 eq by 2050 are expected. The authors concluded that to obtain a larger level of carbon emissions it is essential to implement circular strategies and involve interested parts along the whole aluminum value chain.

Secondary aluminum production requires only around 5 % of energy needed for manufacturing of the metal from mineral raw materials (Gutowski et al., 2013; Takezawa et al., 2015; Wei et al., 2022). Depending on the technology aluminum recycling uses the amount of electricity in the volume of 0.56…2.5 kWh/kg Al depending on the technology (Haraldsson & Johansson 2018). Today recycling of aluminum is € 3 bn market. According to expert assessment (European Aluminium) the 1 mln t of exported aluminum scrap leads to economic losses of around € 960 mln. As aluminum consumption in the European Union increases, the end-of-life aluminum market may grow to a € 12 bn by 2050.

Aluminum processing is a constituent part of a circular economy. It is well known that about 75 % of all the aluminum produced since the Industrial Revolution is still involved either in use or manufacturing (Schlesinger, 2013). Aluminum is capable of being recycled without losing its original properties (lightness, conductivity, formability, permeability etc.) (European Aluminum; Chatterjee, 2007). One of the main tasks for the future is to produce recycled aluminum alloys of high quality. To achieve this goal it is essential to create closed loop recycling (Takezawa et al., 2015; Tu & Hertwich, 2021; Zhu et al. 2021), where a waste of one type is processed into a product of the same type; to develop up-to-date recycling chains with efficient sorting; to implement innovative technologies of treatment of aluminum alloys in order to remove harmful impurities, etc. Fostering the design and manufacturing of secondary from the low-quality scrap is among the priorities of modern (Raabe et al., 2022).

With proper sorting (Capuzzi & Timelli, 2018; Gaustad et al., 2012; Van den Eyndeet al., 2022), scrap and waste of aluminum can be used to make almost any product – from packaging or construction materials to automotive and aircraft details. As a rule to remove impurities and unwanted elements from the structure of secondary aluminum alloys physical separation (air, magnetic, sink float / heavy fraction, eddy current separation, hot crush, color sorting, etc.) is used (David & Kopac, 2015). One of the most promising ways to reduce the energy intensity as well to increase mechanical and operational properties of secondary aluminum alloys is to remove part of the technological operations from the working space of the furnace by using refining (Zhao et al., 2022; Wang et al., 2022; Yu et al., 2022) and modification (Jovičević-Klug et al., 2022; Kotadia et al., 2020; Shin et al., 2012; Yamshynskyi et al., 2022). The possibilities of laser treatment (Bielikov et al., 2015; Mitiaiev et al., 2014) and heat treatment (Hurtalova et al., 2015; Manasijevic et al., 2013; Rady et al., 2020) for structural transformations in the alloys are of great concern.

As a rule recycling leads to obtaining aluminum alloys of comparatively low quality, so adverse technologies on different stages of the production chain should be used. Digitalization and robotics in terms of Industry 4.0 can foster recycling and circular economy practices. For recycling of aluminum the main focus should be on better sorting of scrap, end-of-life products and other waste, materials identification technologies and purification technologies as well.

The researchers (Schlund & Baaij, 2018) carried out a classification of Industry 4.0 technologies dividing them into communication technologies (Machine-to-Machine communication, wireline high-performance network, wireless technologies), embedded systems (sensors, microcontrollers, positioning systems), human-machine interaction (virtual reality / augmented reality, mobile assistance systems), software / systems engineering (cloud computing, big data, real-time data) and smart factory (robotics, industrial smart grids, autonomous and decentral control, etc.). The authors (Cao et al., 2015) presented Aluminum Industry 4.0 Architecture for production and supply chain management, based on visual monitoring; Internet of Things; industrial cloud platform for data management; model-driven and big data driven analyses and decision making; standardization and securitization driven control and management; backtracking process; Cyber-Physical System; real-time perception and intelligent decision making.

A comprehensive literature review on connecting Industry 4.0 technologies to circular economy was carried out (Chauhan et al., 2022). According to the results obtained, the Internet of Things and artificial intelligence have the greatest prospects for the development of a circular economy. Reviews on Industry 4.0 technologies with the emphasis of the possibility of application of the Internet of Things, Virtual Reality and Augmented Reality in remanufacturing was carried out (Kerin & Pham, 2019).

Studying Industry 4.0 solutions in recycling the authors (Penumuru et al., 2020) consider a case of utilization of batteries from electric vehicles. They indicate that cobots can support workers eliminating physical and psycho-physiological harmful and dangerous occupation effects (e.g. by handling aluminum casings and battery modules, performing monotonous unscrewing operations). According to calculations, for a yearly recycling capacity of 3500 items of spent batteries and manual disassembly processes (2 workers), the use of cobots integration may result in a cost reduction of 63,700 € per year. The estimated initial investment is 200,000 €, and it will be needed for approximately three years for the payback.

A digital twin for remanufacturing processes of waste electrical and electronic equipment was developed (Wang & Wang, 2018). Aluminum is widely used in the electrotechnical industry and this solution within a framework of Industry 4.0 may be applied to the recycling of aluminum alloys. The simulated reality, namely simulated annealing, for modeling the process and determining the required parameters of aluminum manufacturing was adopted (Jimenez-Martin et al., 2021).

In the research (Penumuru et al., 2020) machine vision and machine learning technologies for automated aluminum, copper, medium density fiberboard, and mild steel identification were used. In paper (Resti, 2015) the unification of the Principal Discriminant Analysis and Bayes' theorem with images, based on the dependence between edge and color intensity of different aluminum wastes was described. Automatic sorting systems can significantly speed up the aluminum waste classification process.

Smart sorting of aluminum post-consumer scrap into alloys groups is possible with the use of LIBS, Machine Learning and Deep Learning (DL) (Diaz-Romero et al., 2022). For the development and evaluation of DL models for real-time aluminum classification three feature extraction networks were pre-trained, which allowed to process the information from > 200 spectra simultaneously. Previously (Diaz-Romero et al., 2021) the method to classify cast and wrought alloys using transfer learning methods, such as fine-tuning and feature extraction, was presented. Five convolutional neural networks using color and depth images, and transfer learning methods were evaluated. Thus, the presented method can be successfully applied for aluminum sorting and recycling. As the authors (Diaz-Romero et al., 2021, p. 8) point out that "the use of Deep Learning for the sorting of aluminum alloys can be a suitable strategy to eliminate the threat of scrap surplus and significantly increase the value of recycled aluminum".

The other example of linking LIBS and DL for classifying aluminum alloys is a robotic sorting system consisting of a SCARA robot, a vision system, a conveyor and a pneumatic gripper (Engelen et al., 2022). The economic and technical assessment of installation of 2 items of the proposed system, each equipped with 6 robots, had shown that sorting 20,000 t of aluminum with a total added revenue up to 1.95 mln € per year can be reached. Laser Induced Breakdown Spectroscopy (LIBS) used for the manufacturing of secondary aluminum alloys is able to reduce sample preparation times as well as to increase the number of alloying steps for improving the quality of the material (Schlemminger, 2018).

Implementation of Industry 4.0 technologies does not mean the total change of production process and equipment used (Jensen & Remmen, 2017). Data management, the Internet of Things and extended product service systems are linked with the traditional technologies, machines and mechanisms.

New and disruptive business models riven by the use of smart data are emerging around Industry 4.0. Sustainable business models significantly and continuously enhance positive and reduce negative impacts for the environment, that is quite essential for Ukraine. Basic models for circular economy were analyzed by Ruda & Myrka (Ruda & Myrka, 2020). They are 3 R, 10 R, circular suppliers, resources recovery, sharing platforms, product life extension, product as a service etc. The authors (Schumacher et al., 2016) consider Industry 4.0 Maturity Model in dimensions of "Strategy", "Leadership", "Customers", "Products", "Operations", "Culture", "People", "Governance", "Technology". However, the issue of business-models requires more detailed study in the context of aluminum recycling using Industry 4.0 achievements.

Discussion. The literature review and the analysis of the results of the advanced research managed to formulate the following hypotheses that can be applied for metallurgy and machine-building production in Ukraine:

– Industry 4.0 has a favorable effect on circular economy practices.

– Recycling of aluminum has a positive effect on a transition from the linear to the circular economy.

– Circular economy is an instrument for up-to-date operational, environmental and organizational performances of Ukrainian industries.

– Recycling of aluminum has a great potential for implementation of Industry 4.0 technologies.

– Industry 4.0 can be a driving force for innovations in industrially backward and partly destroyed machine-building and metallurgy sectors in Ukraine and for Ukraine recovery as well.

The author did not find the relevant research / publications that incorporate a general evaluation of Industry 4.0 and circular economy in combination with each other and in relation to recycling of aluminum alloys that determines directions for further research.

Conclusions. Linking Industry 4.0 with circular economy paradigm indicates a positive effect on sustainable development. Aluminum is a perfect circular metal, which can lead to low-carbon manufacturing and zero waste production. Recycling is a promising direction due to expected lower costs and decreased environmental effects. It is expected that the introduction of innovations based on Industry 4.0 in the process of aluminum recycling will reduce Ukraine's dependence on imports, increase the competitiveness of the economy and level of the industrial development, facilitate disposal of large streams of scrap and, in general, will contribute to the recovery of Ukraine.

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Впровадження стратегій Індустрії 4.0 та циркулярної економіки в переробці алюмінієвого брухту

В сучасних економічних і соціально-політичних умовах в Україні особливого значення набувають зниження імпортозалежності та собівартості виробництва, збереження навколишнього середовища, а також утилізація потоків металобрухту. Країна практично втратила власне виробництво алюмінію, тоді як алюміній широко використовується в усіх галузях промисловості; додатково очікується значна кількість алюмінієвого брухту в результаті військових дій. Алюміній – циркулярний матеріал, який не втрачає властивостей при переробці. Одним із шляхів покращення економічної ситуації в Україні та переходу до циркулярної економіки є виробництво алюмінієвих сплавів із вторинної сировини та виробів з них. Рециклінг потребує тільки близько 5 % енергії, необхідної для виробництва первинного металу, що приводить до значного зниження викидів парникових газів, економічної ефективності та збереження природних ресурсів. Циркулярність відіграє провідну роль у досягненні цілей сталого розвитку. Виробництво вторинних алюмінієвих сплавів вважається сталим видом діяльності. Однак використання алюмінієвих сплавів вторинних, отриманих рециклінгом, для виготовлення відповідальних деталей, наприклад таких, що використовується в авіаційній та автомобільній промисловості, можлива при застосуванні ефективних сортування та металургійної переробки. Літературний пошук показав, що серед найбільш перспективних технологій Індустрії 4.0 щодо рециклінгу алюмінію є Інтернет речей, віртуальна реальність, доповнена реальність та штучний інтелект. Передовий світовий досвід рециклінгу алюмінію довів ефективність використання симуляції реальності, зокрема імітаційної термообробки, яка є невід'ємною частиною технології виробництва алюмінієвих сплавів. Машинне бачення та машинне навчання важливі для сортування металобрухту, здійснення його класифікації. Широкий спектр досліджень присвячений особливостям застосування лазерно-індукованої спектроскопії пробою, що забезпечує "розумне" сортування алюмінієвого брухту. Деякі технології Індустрії 4.0 важливі в контексті безпеки праці: цифрові близнюки можуть надавати рекомендації щодо виконання роботи, коботами можна ліквідувати фізичні та психофізіологічні шкідливі та небезпечні виробничі фактори, які впливають на людину тощо. Циркулярна економіка (шляхом рециклінгу) та Індустрія 4.0 є перспективними рішеннями для пом'якшення негативних наслідків виробництва. Було проаналізовано потенціал і проблеми, пов'язані з об'єднанням цих двох парадигм із вторинним виробництвом, що означає впровадження Індустрії 4.0 в рециклінг алюмінію.

Ключові слова: *алюміній, рециклінг, Індустрія 4.0, циркулярна економіка, сталий розвиток.*