RESEARCH AND ENGINEERING INNOVATION PROJECTS OF THE NATIONAL ACADEMY OF SCIENCES OF UKRAINE

https://doi.org/10.15407/scine20.03.040

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DEVELOPMENT OF TITANIUM PRODUCTION IN UKRAINE: EVOLVING PROSPECTS BASED ON NATIONAL R&D

Introduction. *The development of Ukraine's resource potential in the field of mining and advanced processing of titanium raw materials is one of the important components of countering military threats and the national economy recovering based on new technologies.*

Problem Statement. *The realities of wartime reinforce the importance of domestic resource involvement to resumption of the titanium products complete production cycle in Ukraine, which can facilitate integration into global value chains.*

Purpose. *To determine the directions of titanium production development in Ukraine based on the available resource and production potential, foreign and domestic R&D.*

Materials and Methods. *The authors have used data of statistical observations of the State Statistics Service in Ukraine, the U.S. State Geological Survey, the World Intellectual Property Organization; methods of systematic approach, economic and statistical, calculation and design, graph analytical methods, statistical comparisons and grouping, systematic and comparative analysis.*

Results. *The possibilities of realizing resource, production, and R&D potential for deep processing of titanium metal in Ukraine have been substantiated. The directions of the Ukrainian titanium industry development have been offered. The construction of new and/or modernization of production facilities for processing Ukrainian titanium raw materials based on domestic scientific developments has been substantiated.*

Conclusions. *Ukraine has a strategic potential to create a full cycle of titanium products production. Providing favorable conditions for attracting investment and access to capital and financial and economic instruments facilitates technological modernization. This, in turn, will help open "a window of opportunities" for Ukraine for manufacturing titanium products with high added value for the needs of the military industrial complex and other high-tech industries.*

Keywords: titanium, resource potential, production modernization, research and development, titanium manufacturing, global value chains.

Citation: Venger, V. V., Bykonia, O. S., Hakhovych, N. G., Kushnirenko, O. M., and Tsyplitska, O. O. (2024). Development of Titanium Production in Ukraine: Evolving Prospects Based on National R&D. *Sci. innov.*, 20(3), 40—52. https://doi.org/10.15407/scine20.03.040

The extremely difficult historical challenge of surviving a full-scale military invasion has made Ukraine address the task of preserving its identity, liberating its territory from the invaders, and providing opportunities for normal life and development of the nation. All this depends on a powerful economic component — the restoration of the industrial base to meet the needs of the civilian population and the Armed Forces of Ukraine. In these conditions, it is extremely important to realize internal opportunities for industrial development, in particular in those industries where Ukraine has sufficient resource, production, scientific, personnel, and export potentials. The establishment of a full cycle of goods production made of titanium ores and concentrates as a critically important mineral for national security, in particular metal titanium, is one of these directions.

Titanium is used in a number of strategically important activities: aerospace industry (high strength and relatively low weight of titanium make it suitable for frames of aircraft bodies (airplanes) in combination with aluminum; heat resistance allows it to be used in turbofan engines); the defense industrial complex (naval ships and submarines use titanium's corrosion resistance underwater, and surface vehicles such as tanks are coated with titanium parts); medicine (medical implants and prosthetics, artificial joints, spinal devices and dental implants); mechanical engineering (seawater desalination plants); renewable energy (production of lithium-titanium batteries; provision of geothermal power plants). For its unique properties titanium is called the material of future, and the country utilizing it for production can become a valuable participant in global economic relations.

Ukraine has unique reserves of titanium ores. However, the advanced level of their processing and production of products with high added value is limited by many factors, in particular: a significant share of the export of titanium ores, concentrates and titanium sponge (more than 80%); insufficient production capacity for deep processing of titanium ingots; structural imbalance of products; the need to modernize the industry's production potential; high risks associated with hostilities in Ukraine. The vast majority of titanium ores and concentrates produced in Ukraine are not processed into products with a higher added value, which determines the urgency of finding strategic solutions to stimulate the development of the full cycle of production of titanium products for the domestic market and inclusion in the global value chains.

For many years, scientific schools in the field of solid state physics, metallurgy. and physical materials science have been developing in Ukraine. In their activity, research into the specifics of titanium mining, smelting, and processing occupies one of the important places. In particular, Full Member of the National Academy of Sciences of Ukraine O. M. Ivasyshyn, Director of the G. V. Kurdyumov Institute of Metallurgical Physics of the NAS of Ukraine (2011—2019) studied the problems of enhancing the mechanical characteristics of structural titanium alloys. He trained a generation of talented researchers who created a powerful experimental base of titanium alloy processing technologies, which reached the highest (record) strength indicators in the world, up to 1900 MPa [1].

A wide range of scientific theoretical and applied problems has been investigated by representatives of the scientific school of the Paton Electric Welding Institute. S. Akhonin, V. Bilous, V. Pashynskyi, S. Shvab, and other researchers created a line of industrial electron beam installations with a capacity of 180 to 1500 tons of titanium ingots per year. All these installations are equipped with *Paton-300* thermocathode electron guns with a power of 300 kW and an accelerating voltage of 30 kV. The UE5810 industrial electron beam installation with a total capacity of 2.5 MW is equipped with 7 *Paton-300* electron guns and is designed for melting titanium ingots with a diameter of up to 1100 mm and a weight of up to 20 tons [2].

Researchers from the Frantsevich Institute of Problems of Materials Science of the NAS of Ukraine M. Karpets, S. Firstov, O. Rakytska, N. Krapyvka have presented developments in the field of research of new titanium alloys, in particular the regularities of structure formation of quasicrystals and approximant crystalline phases in titanium alloys [3].

In Ukraine, the technology of electron beam melting of titanium alloys has been developed, which ensures the guaranteed removal of refractory inclusions, the fine-grained structure of the ingot, and the homogeneity of the distribution of alloying elements in the volume of the ingot. According to this technology, up to 100% titanium scrap and spongy titanium can be used as an initial charge without its prior pressing into a consumable electrode. The developed technology makes it possible to obtain both traditional industrial titanium alloys, known since the last century, and new complex alloyed high-strength titanium alloys for structural purposes and heat-resistant titanium alloys with dispersion strengthening with silicides and intermetallics, which are created by researchers of the National Academy of Sciences of Ukraine [4]. The newly created low-carbon technology for the production of titanium powder is stated in the study of Ukrainian specialists Gonchar et al., representing *Titanera* LLC, *Velta* Holding US Inc [5].

Among the foreign researchers who have dealt with studying the directions for improving the manufacturability of titanium, the developments of William Kroll who invented the process for the production of titanium and zirconium called the "Kroll process", which remains the main way of extracting these metals from ores, should be mentioned first [6]. Banerjee and Williams examine the science and technology prospects of titanium in safety-critical structures such as aircraft and aircraft engines [7]. Researchers from the U.S. National Academy of Sciences' National Materials Advisory Board Jaffee et al have devoted much work to the current use and rationale for future opportunities, including the economic aspects of titanium materials [8]. In turn, the work of Agrippa and Botef summarizes traditional and new technologies for obtaining titanium and titanium alloys in the context of the growing challenges of the future [9].

In general, WIPO in its report [10] has indicated several thousand patent families filed in the world between 2012 and 2022 in the field of application of titanium dioxide and metallic titanium, in particular: 2027, in ceramics; 1874, in the production of electrodes; 1182, in medical technologies; 953, in cosmetics; 908, in the production of various types of coatings; 719, for water treatment. China and Japan have been the largest applicants, while Ukraine ranks 10th by the number of issued patents (12).

Chinese researchers have published many studies on titanium production technologies. Scholars from School of Minerals Processing and Bioengineering of Central South University in Changsha, China — Qiu and Guo have substantiated the tendencies of Chinese titanium industry development and defined the strategic aspects of its development: the creation of joint production in the steel and titanium industries, combining the advantages of steel production and non-ferrous metal smelting, as well as strengthening the large-scale production of titanium alloys in the PRC [11].

In 2022, the Japanese company Nippon Steel announced the creation of an advanced technology for the production of *TranTixxii™-Eco* titanium products. This is an ecological technology of combining electron-beam melting and the use of titanium scrap, which made it possible to reduce carbon dioxide emissions by more than 50%. In particular, the technology is used for the aviation industry (production of premium class gliders and engines). In addition, the company has organized the production of almost the entire spectrum of titanium products and uses an integrated production process (melting, forging, hot rolling and cold rolling) [12].

Canadian University of Sherbrooke researchers El Khalloufi et al. made an overview of effective methods for the production of titanium powder using the processes of extractive metallurgy and substantiated the prospects for their future development [13]. And in the work of Nyamekye et al.

it is established that additive manufacturing is the direction of development of titanium powder processing that will reduce harmful effects and increase the resource efficiency of technologies [14]. Also, further progress in the formation of sustainable value-added chains from titanium is being considered by some U.S. companies (*IperionX* Ltd., *ELG Utica Alloys*) in the context of creating a low-carbon value-added chain from 100% recycled titanium, as stated by Toto [15].

The necessary conditions for the involvement of countries that are mainly exporters of titanium raw materials in the higher links of global chains of added value are revealed in the work of Roux et al. [16] on the example of African countries. In particular, the key condition is the development and implementation of the latest technologies for advanced processing of titanium raw materials. The authors also point to the fragmentation of titanium value-added chains in the world due to the complexity of the titanium production process, the negative impact on the environment, the availability of technologies and the remoteness of markets.

In mentioned studies, a significant contribution was made to expanding the possibilities of using titanium as a structural material of the future. At the same time, in the scholarly research discourse, the issues of Ukrainian titanium industry restoration to ensure the needs of defense capability and stability of the national economy, as well as access to the higher links of value-added chains in the world, remain insufficiently investigated.

Determination of prospects and directions of development of metal titanium production in Ukraine on the basis of available resource and production potential, global and domestic scientific developments.

A systematic approach was used to determine the links between phenomena and processes of economic reality. In the research the monographic method for the study and analysis of literary sources, legislation, business experience in modern conditions is used; economic and statistical method was implemented for processing official statistical data on the international, national, and regional levels; system and comparative analysis was applied to the indicators of the titanium industry development; design calculation method was used for evaluation the economic effects of competitive titanium production technologies introduction in Ukraine; techniques of statistical comparisons, grouping, graph and analytical method were utilized in the study as well.

1. THE CURRENT STATE OF THE TITANIUM INDUSTRY OF UKRAINE

Why is titanium called the structural material of the future? The answer to this question is related to its technical characteristics and possibilities of application in many areas of social economic life. Here are some of the properties that naturally make titanium superior to traditional materials like stainless steel and aluminum [17]:

- high strength-to-weight ratio: titanium is twice as strong as aluminum and 45% lighter than steel of comparable strength;
- corrosion resistance: titanium's natural resistance to corrosion allows it to be used in harsh conditions, including seawater;
- distribution: titanium is the 9th most common element in the earth's crust, which is found in almost all rocks and sediments [18];
- biocompatibility: the inertness of titanium inside the human body makes it biocompatible and suitable for medical and dental implants;
- heat resistance: titanium has a melting point of 1670 °C and can withstand a wider range of temperature as compared with stainless steel and aluminum.

Production activity in the titanium industry is concentrated in the pigment titanium dioxide (TiO_2) sector, which consumes 90—95% of ores and concentrates and is the final link in the production chain for the production of titanium whites and the production of paint and varnish materials, paper, plastics, ceramics and other products. The other 5—10% of titanium raw materials are used for metal smelting, from which a wide range

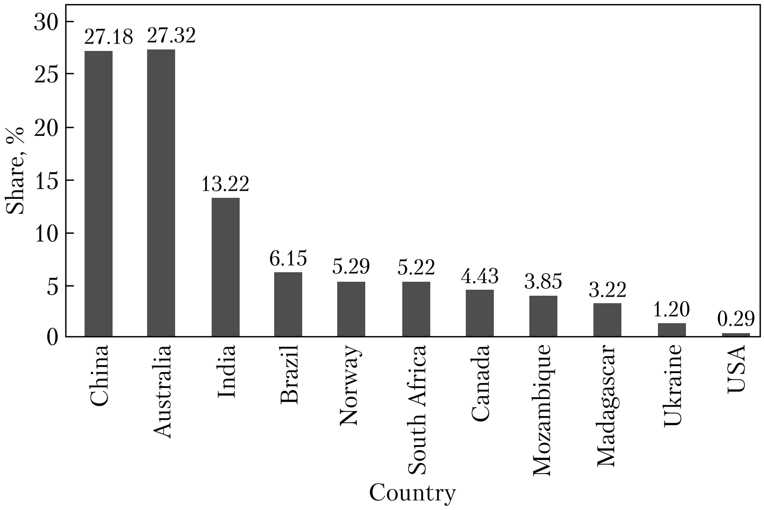

Fig. 1. The structure of world reserves of titanium (ilmenite, rutile) as of 01.01.2022

Source: compiled according to the U.S. Geological Survey [21].

of products can be produced: castings, forgings, bars, pipes, wire, etc.

Titanium is the fourth most abundant structural metal, accounting for 0.6% of the Earth's crust [19]. In 2023, the world titanium market is estimated at USD 28 billion. It is expected that the market will expand at a significant rate and will reach about USD 52.5 billion before 2033 [20]. Explored areas of titanium ores are present all over the world and include deposits in the People's Republic of China, Australia, India, Brazil, Norway, South Africa, Canada, Mozambique, Madagascar, Ukraine, the USA, and other countries (Fig. 1).

As Fig. 1 shows, Ukraine has enough titanium raw materials to form the complete production cycle of titanium products, starting from the extraction of titanium-bearing ores, their enrichment and production of sponge titanium prior to the smelting of titanium alloy ingots and the production of a wide range of titanium semi-finished products such as castings, forgings. Titanium ores in Ukraine are represented by 27 deposits and more than 30 ore occurrences of varying degrees of exploration [22]. According to the U.S. State Geological Survey, reserves of titanium ores (ilmenite, rutile) in Ukraine at the end of 2021 amounted to 8,400 thousand tons (same as in 2020), of which 5,900 thousand tons of ilmenite and 2,500 thousand tons of rutile [21].

By Decree of the President of Ukraine dated July 23, 2021 No. 306/2021 on the Decision of the National Security and Defense Council of Ukraine dated July 16, 2021, on stimulating the search, extraction and enrichment of minerals of strategic importance for the sustainable development of the economy and the defense capability of the state, titanium ores were included in the list of strategic metal ores.

In 2021, the production of titanium concentrates in Ukraine amounted to 525 thousand tons, out of which the production of ilmenite concentrate accounted for 430 thousand tons, by 34 thousand tons more than in 2020 (5.11% of world production), while the production of rutile concentrate made up 95 thousand tons (15.10% of world production), according to estimates of the U.S. State Geological Survey [21]. The total production of titanium concentrates in Ukraine in 2021 was estimated at 5.81% of world production.

Most of titanium ores and concentrates produced in Ukraine (over 80%) are exported (Fig. 2). In 2021, Ukraine increased the export of titanium-containing ores and concentrate by 3% as compared with 2020 to 553.05 thousand tons. In monetary terms, during this period, exports (at an average price of USD 265/t) increased by 17% to USD 161.9 million.

Geographically, Ukrainian titanium ores and concentrates were exported to more than 50 countries around the world. Among the countries that purchased Ukrainian titanium ores and concentrates, 3 categories can be distinguished: main partners (supply from 50 thousand tons per year), average consumers (from 1 to 50 thousand tons per year), small consumers (up to 1 thousand tons per year). To the main partners can be assigned in 2017—2021: Czech Republic (116.9 thousand tons); China (average total purchase for the period 61.7 thousand tons), which purchased from Ukraine in 2021 up to 115.6 thousand tons; Mexico (overall 85.6 thousand tons); russian federation (74.5 thousand tons); USA (58 thousand tons); Türkiye (68.7 thousand tons). In total, the share of these countries in the export basket is more than 80%. The second category included: Belarus, Great Britain, Egypt, India, Spain, Kazakhstan, the Netherlands, the Republic of Korea, Romania, Hungary, France. These countries had a share of up to 16.5% cumulatively during 2017—2021. Other countries consumed small quantities, in particular, the countries of Europe, Asia, and the Middle East. They accounted for up to 3.5% of the total exports of titanium ores and concentrates.

About 3% of the mined ore and concentrates is used to produce titanium sponge. In Ukraine, titanium sponge is produced by Zaporizhzhia Titanium-Magnesium Plant LLC, State Enterprise NPC *Titan*, Paton IEW, MK *Antares*, *Strategy* BM LLC. The production of titanium sponge in 2019 decreased more than 3 times as compared with 2008 and tended to further decline (from 8 thousand tons in 2019 to 6.1 thousand tons in 2021). This segment also maintains a significant export orientation — almost 90% of the titanium sponge produced in 2021 was exported (Fig. 3) at a price that is 28 times higher than the export price of 1 ton of titanium ores and concentrates (Table 1).

These data indicate the feasibility of reorientation of ore and concentrates exports to domestic consumption for increasing of titanium sponge production, part of which it is advisable to use,

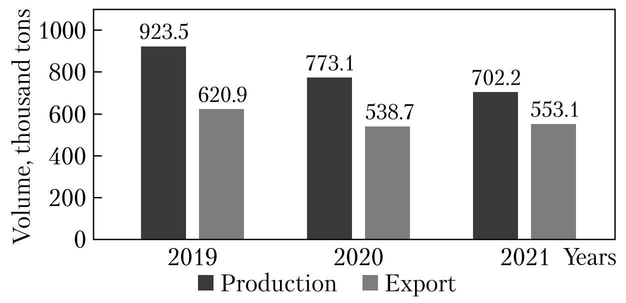

Fig. 2. Production and export of titanium concentrates (ilmenite and rutile) in Ukraine for 2019—2021

Source: compiled according to the State Statistics Service [23].

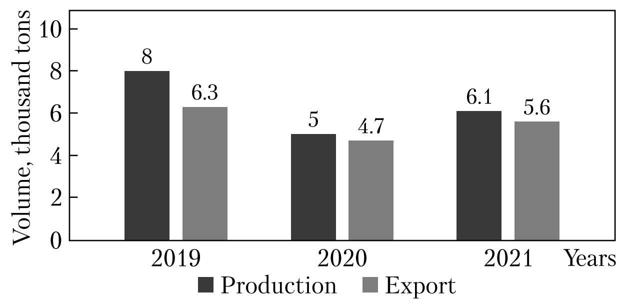

Fig. 3. Production and export of titanium sponge in Ukraine for 2019—2021

Source: compiled according to the State Statistics Service [23].

in turn, for domestic consumption and the production of titanium ingots and other products from it with a higher degree of added value. The production of titanium ingots in Ukraine can reach 6—8 thousand tons (the price of 1 ton of ingots is 64 times higher than the price of 1 ton of ores and concentrates).

With the existing export product range (titanium ores and concentrates, titanium sponge), the opportunity to increase revenues by supplying products with higher added value (titanium ingots, profiles, wire, plates, pipes and tubes) to foreign markets is missed. At the same time, the average price of 1 ton export raw titanium and powders (UKTZED 810820) is 28.0 times higher as compared with that of titanium ores and concentrates (UKTZED 261400); 36.8 times higher as compared with that of titanium and titanium products, including waste and scrap (UKTZED 810800); 92.4 times higher as compared with that of products made of titanium (rods, bars, profiles, wire, plates, sheets, tape, foil, pipes and tubes), in particular, 197.9 times higher as compared with that of pipes and tubes (UKTZED 81089060) (Table 2).

This indicates the need to modernize existing and/or to build new production facilities in order to introduce advanced processing of titanium in Ukraine to obtain a significantly greater economic effect than from the export of titanium ores and concentrates. For example, from 1 ton of ilmenite (with a titanium concentration of 56%) can be obtained 0.7 tons of titanium slag with a titanium dioxide content of up to 80% [24], the price of which is 1.4 times higher than the price of 1 ton of ilmenite [25]. From 1 ton of titanium slag can be obtained 0.33 tons of titanium sponge,

Table 1. **Balance of Ores and Concentrates of Titanium and Titanium Sponge**

Indicator	Year		
	2019	2020	2021
Titanium ores and concentrates			
Reserves, thousand tons*	8,400	8,400	8,400
including ilmenite reserves, thousand tons	5,900	5,900	5,900
rutile reserves, thousand tons	2,500	2,500	2,500
Production of ilmenite concentrates, thousand tons**	≈738.8	773.1	702.2
Production of rutile concentrates, thousand tons**	184.7	n/a	n/a
Export of all ores and concentrates, thousand tons**	620.9	538.7	553.1
Import of all ores and concentrates, thousand tons**	0.8	1.0	1.2
The share of exports of all ores and concentrates in the total production (potential for the development of the domestic market), %	≈84.0	≈69.7	≈78.8
Apparent consumption of concentrates on the domestic market (production – export + + import), thousand tons ***	≈118.8	≈235.4	≈150.3
The share of internal consumption of all ores and concentrates to the total production, %***	≈16.0	≈30.3	≈21.2
Foreign exchange earnings from the export of ores and concentrates, USD million / average price of 1 ton, USD per ton	154.9 / 249.5	138.3 / 256.7	161.9 / 292.7
Titanium sponge (sponge titanium)			
Production of titanium sponge in Ukraine, thousand tons**	8.0	5.0	6.1
Export of titanium sponge, thousand tons**	6.3	4.7	5.6
Import of titanium sponge, thousand tons**	2.4	0.8	0.3
The share of titanium sponge exports in the total production (potential for the development of the domestic market), %	78.8	94.0	91.8
Apparent consumption of titanium sponge in the domestic market (production – export + + import), thousand tons***	4.1	1.1	0.8
The share of domestic consumption of titanium sponge to the total production, % ***	51.3	22.0	13.1
Foreign exchange earnings from the export of titanium sponge, USD million / average price of 1 ton, USD per ton	52.4 / 8,317.5	31.6 / 6,723.4	40.9 / 7,303.6

Note: n/a – data not available; * – compiled according to the data [21]; ** – compiled according to the data [23].

the cost of which is 8—9 times higher than the cost of 1 ton of ilmenite. About 0.33 tons can be produced from titanium sponge, but this is a titanium billet, the cost of which is 24.8 times higher than the cost of 1 ton ilmenite. Provided that production of titanium products is organized for the aerospace industry, energy, military sector and medicine, product prices are rising even more. While Ukraine exports mainly titanium ores and concentrates, as well as titanium sponge, foreign manufacturers importing these products deepen their processing and then sell titanium products with higher added value on world markets, ensuring the effective development of not only individual enterprises for the production and use of titanium, but also their economies as a whole. For example, China, consuming a fifth of Ukrainian exports, is the largest importer of titanium raw materials, which it processes into titanium sponge and subsequently consumes in higher stages.

Trends have been identified that indicate the need to make decisions on ongoing strategic initiatives for the construction of new and reconstruction of existing enterprises of the Ukrainian titanium industry.

2. PROMISING DIRECTIONS FOR EXPANDING THE PRODUCTION OF TITANIUM PRODUCTS IN UKRAINE

To realize the potential of the titanium industry in Ukraine, it is advisable, together with investors, to build and/or to modernize production facilities that will be able to process domestic titanium raw materials, covering the needs for titanium products for the domestic and foreign markets.

It should be noted that modernization and/or new production facilities should be launched on the basis of:

- technologies for the production of rods with a diameter of 200 mm. Traditionally, semi-finished products in the form of titanium rods are produced by melting ingots of large diameter (600 mm) using the vacuum arc remelting

Table 2. **Ratio of the Average Export Price of Titanium Ores and Concentrates to the Average Export Price of Titanium Products, 2019—2021**

Product	The average price of 1 ton of exports in 2019—2021, USD	The ratio of the average price of 1 ton of export products to the average price of 1 ton of titanium ores and concentrates, times	The ratio of the average export price of 1 ton of products to the average export price of titanium ores and concentrates required for the production of 1 ton of products, times
Titanium ores and concentrates UKTZED 261400	266	—	—
Titanium and titanium products, including waste and scrap UKTZED 810800	9,784	36.8	2.3
Titanium is untreated; powders UKTZED 810820	7,450	28.0	1.8
Titanium products, n.v.i.u.: rods, bars, profiles, wire, plates, sheets, tapes, foil, pipes and tubes	24,578	92.4	5.8
including pipes and tubes UKTZED 81089060	52,634	197.9	12.4
Pigments and preparations made on the basis of titanium dioxide (with a content of at least 80 wt. %) UKTZED 320611	1,956	7.4	3.7

Source: authors' calculations based on State Statistics Service [23].

(VAR) method, and then reforging them into forgings of smaller diameter (up to 200 mm) and subsequent rolling or pressing. Ingots are smelted using electron beam melting (EBM) technology with a diameter of 300 to 1100 mm in Ukraine. Based on the developments of the "Paton Electric Welding Institute of NAS of Ukraine", from economic point of view, it is more expedient to smelt ingots with a diameter of up to 200 mm, while eliminating the cost operation of reforging the ingot from the technological process, and then produce rods with a diameter of up to 60 mm, which will reduce the cost of final products by 10—15% and would enable them in 3D printing technology;

- production of parts of a given shape and structure with pre-predicted properties based on promising developments of additive technologies in the Paton Electric Welding Institute of the NAS of Ukraine. The advantages of the proposed developments are: lower cost of a 3D printer compared with foreign analogs, full scientific support and maintenance, using of own titanium raw materials and semi-finished products. Expanding the range of products with high added value through the development of new additive technologies is their application, including in the aviation industry. According to *Boeing* forecasts, 3D printing of titanium parts on a printer would save USD 2 to 3 million for each *787 Dreamliner* aircraft. Of USD 256 million cost of *787 Dreamliner* aircraft, USD 17 million is spent on titanium parts production.

3D printing is also used to produce products for the medical field: transparent aligners (aligners) for straightening teeth; surgical templates to help perform complex implant surgeries. 3D technologies are also actively used in surgery, in particular in knee replacement. In 2022, the global market for medical products made with the use of 3D printing reached USD 2.8 billion. In 2032, it may grow up to USD 11.0 billion [26].

Paton Electric Welding Institute of NAS of Ukraine has already developed and proposed innovative technologies for layer-by-layer manufacturing of titanium products using the rapid prototyping method, which open up new opportunities for 3D printing of parts for gas turbine engines of aircraft and the manufacture of endoprostheses. In addition, 3D printing technology will make it possible to produce products that cannot be obtained by other methods and compete with foreign samples;

- production of titanium goods based on the VAR technology of titanium ingots for use in the production of highly loaded aircraft parts. Since, according to the requirements of the design documentation, ingots produced using the EPP technology used in Ukraine must be further subjected to VAR in certified furnaces, there is an objective need and economic feasibility for expanding production capacity by purchasing and using furnaces based on VAR technology. The range of production of titanium end-use products in the aviation industry can be expanded. The demand for such products will grow annually, since it is estimated that by 2035 the number of commercial aircraft alone will double in comparison to 2014, and products made from titanium alloys will continue to be the main material for their use in the aviation industry in the future. The organization of domestic production of titanium ingots based on VAR will make it possible to join the global value chains of the aviation industry. The estimated investment to launch the production of titanium products based on VAR will be about USD 11 million. The production of aircraft titanium ingots, which can be produced in Ukraine, will have a price competitive advantage of an average of 18—32% as compared with world analogs, which will allow them to successfully compete in world markets;
- development of Ukrainian rolling production for sheet rolling, in particular, a rolling shop with associated heating furnaces, a pickling department and a chemical laboratory. Their cost can range from USD 250 to 500 million.

Taking into account the growing needs of the defense complex of Ukraine and the prospects for joining NATO, domestic consumption of titanium ores and concentrates can be increased by establishing the production of materials and components for military aviation, rocketry, production of armor, warships, and ammunition (Table 3).

Titanium alloys Ti-6AL-4V and Ti-6AL-4V ELI are the main material for defense production. As of June 2023, on the world market one ton of such alloys cost from USD 15 to 50 thousand depending on the form of release and other parameters.

Recently, the formation of global titanium chains has been increasingly affected by trade wars, as well as instability generated by russian aggression in Ukraine, due to which Western partners are looking for alternative sources of supply of titanium products with higher added value. Ukraine has strategic potential in the development of the titanium products production, in particular, a unique resource base, production assets, developed scientific schools and a personnel training system for the needs of the industry.

The existing potential is not used due to the lack of a full production cycle and high raw material export orientation. Establishing a full cycle of processing titanium ores and concentrates will provide significant economic effects, from a multiple increase in value added to a growth in jobs and tax revenues to budgets of all levels.

Domestic research and development can become the basis for the modernization of industry enterprises or the launch of new projects of advanced processing producing titanium products considering the achievement of the Sustainable Development Goals. The promotion of support for R&D depends on co-financing of joint research projects with business and foreign partners.

The existing potential opens a window of opportunity for Ukraine to integrate into the global supply chains of the aviation and other industries and become a reliable supplier of titanium products in the world.

FUNDING OF THE RESEARCH

The study was funded by the National Academy of Sciences of Ukraine within the research project "Innovative modernization of prospective industries of Ukraine in the postwar period based on the existing R&D, production and resource potential" (state registration number 0123U102325).

Table 3. **Directions for Using Titanium and Titanium Alloys for Military Purposes**

No.	Material	Product
1	Ti-6AL-4V (titanium-aluminum-vanadium alloy)	Tank armor, body armor
2	Ti-6AL-4V ELI (titanium-aluminum-vanadium alloy with ultra-low impurity content)	Aircraft turbines and other equipment exposed to high temperatures. Military medicine (prostheses, artificial joints, instruments)
3	6AL-6V-2Sn-Ti (aluminum-vanadium-tin-titanium alloy)	Components of ammunition and frames, less often — components of the chassis and missile bodies
4	Titanium composite (titanium + fiberglass)	Helicopter propeller blades
5	TiAl (titanium aluminide)	Blades of turbojet engines
6	Titanium and titanium alloys	Military aircraft construction (frames, bodies, wind access panels, landing gear, brackets) Military shipbuilding (propeller shafts and underwater manipulators on ships, rigging equipment, cooling systems and pipelines, underwater ball valves and heat exchangers, fire pumps)

Source: compiled by the authors based on data [27, 28].

ACKNOWLEDGMENTS

The authors express their gratitude to Sviatoslav Gnyloskurenko, senior researcher of the Physical and Technological Institute of Metals and Alloys of the NAS of Ukraine for productive discussion regarding Kroll's process of titanium production.

REFERENCES

1. Markovskyi, P. E., Savvakin, D. G. (2021). An outstanding personality of titanium science. To the 75th anniversary of Academician of the National Academy of Sciences of Ukraine O. M. Ivasyshyn. *Bulletin of the National Academy of Sciences of Ukraine,* 11, 84—89. https://doi.org/10.15407/visn2021.11.084 [in Ukrainian].
2. Akhonin, S. V. (2019). Trends in the development of special electrometallurgy of titanium in Ukraine. *Bulletin of the National Academy of Sciences of Ukraine,* 6, 28—36. https://doi.org/10.15407/visn2019.06.028 [in Ukrainian].
3. Karpets, M. V., Firstov, S. O., Rokytska, O. A., Krapyvka, N. A. (2016). The effect of titanium on the phase composition of alloys of the Ti—Cr—Al—Si—O system. *International scientific conference "Materials for work in extreme conditions — 6" (1—2 December, 2016, Kyiv)*. Kyiv, National Technical University of Ukraine Igor Sikorsky Kyiv Polytechnic Institute, 309—312 [in Ukrainian].
4. Firstov, S. A. (2004). *The main tendencies in elaboration of materials with high specific strength*. In: Metallic materials with high structural efficiency. Dordrecht: Kluwer Academic Publishers.
5. Gonchar, A., Troshchylo, V., Brodskyy, A., Yarovynskyi, V., Chukhmanov, O. (2023). Development of a technology to produce titanium powder with a low carbon footprint. *Eastern-European Journal of Enterprise Technologies*, 2(6) (122), 42—54. https://doi.org/10.15587/1729-4061.2023.276746
6. Kroll, W. (1940). The Production of Ductile Titanium. *Transactions of the Electrochemical Society*, 78(1), 35—47. https://doi.org/10.1149/1.3071290
7. Banerjee, D., Williams, J. C. (2013). Perspectives on Titanium Science and Technology. *Acta Materialia,* 61(3), 844—879. https://doi.org/10.1016/j.actamat.2012.10.043
8. Jaffee, I. R., Burte, H. M. (1973). *Titanium Science and Technology.* Springer New York, NY. https://doi.org/10.1007/978-1-4757-1346-6
9. Agripa, H., Botef, I. (2019). *Modern Production Methods for Titanium Alloys: A Review.* In: Titanium Alloys — Novel Aspects of Their Manufacturing and Processing. (Eds. Maciej Motyka, Waldemar Ziaja and Jan Sieniawsk). https://doi.org/10.5772/intechopen.81712
10. WIPO (2023). Production of titanium and titanium dioxide from ilmenite and related applications. Patent Landscape Report. URL: https://www.wipo.int/edocs/pubdocs/en/wipo-pub-1077-23-en-patent-landscape-report-ilmenite.pdf (Last accessed: 28.08.2023).
11. Qiu, G., Guo, Y. (2022). Current situation and development trend of titanium metal industry in China. *Int. J. Miner. Metall. Mater.*, 29, 599—610. https://doi.org/10.1007/s12613-022-2455-y
12. Yatsunami, Y., Takanashi, K. (2022). Manufacturing Technology of Titanium and Titanium Alloys. *Nippon Steel Technical Report No. 128*, March. URL: https://www.nipponsteel.com/en/tech/report/pdf/128-02.pdf (Last accessed 18.08.2023).
13. El Khalloufi, M., Drevelle, O., Soucy, G. (2021). Titanium: An Overview of Resources and Production Methods. *Minerals*, 11(12), 1425. https://doi.org/10.3390/min11121425
14. Nyamekye, P., Golroudbary, S. R., Piili, H., Luukka, P., Kraslawski, A. (2023). Impact of additive manufacturing on titanium supply chain: Case of titanium alloys in automotive and aerospace industries. *Advances in Industrial and Manufacturing Engineering,* 6, 100112. https://doi.org/10.1016/j.aime.2023.100112
15. Toto, D. (2023). Companies partner on recycled titanium supply chain. *Recycling today*, July 11. URL: https://www.recyclingtoday.com/news/aperam-recycling-iperionx-parter-on-titanium-supply-chain/ (Last accessed: 04.08.2023).
16. Roux, R. N., Van der Lingen, E., Botha, A. P., Botes, A. E. (2020). The fragmented nature of the titanium metal value chain. *Journal of the Southern African Institute of Mining and Metallurgy*, 11(120), 633—640. https://dx.DOI.org/ 10.17159/2411-9717/1126/2020
17. Bhutada, G. (2023). Titanium: The Metal of the Future. *Visual Capitalist*, January 5. URL: https://www.visualcapitalist.com/sp/titanium-the-metal-of-the-future/#:~:text=Titanium%20is%20as%20strong%20as,products%20stronger%20and%2For%20lighter (Last accessed: 14.08.2023).
18. Bedinger, G. M. (2013). Titanium. *Mining Engineering*, July. URL: https://pubs.usgs.gov/publication/70047016 (Last accessed: 14.08.2023).

19. Sana, I. (2023). *Titanium Reserves by Country and 10 Biggest Mines in the World*. June 12. URL: https://shorturl.at/fjN15 (Last accessed: 17.08.2023).
20. Titanium Market Analysis Report (2023 to 2033) / Fact. MR. 2023. URL: https://www.factmr.com/report/titanium-market (Last accessed: 17.08.2023).
21. U.S. State Geological Survey. (2023). *Mineral Commodity Summaries*. URL: https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-titanium-minerals.pdf (Last accessed 18.08.2023).
22. Data portal of the mining industry of Ukraine. (2021). Titanium ores. URL:_https://eiti.gov.ua/resursi-rozvidka-ta-vidobuvannya/rudi-titanu/#:~:text (Last accessed 18.08.2023).
23. State Statistical Service of Ukraine. (2023). URL: https://www.ukrstat.gov.ua/ (Last accessed 18.08.2023).
24. Chen, G., Chen, J., Srinivasakannan, C., Peng, J. (2012). Preparation and Structural Characterizations of Titania Slag. *High Temp. Mater. Proc.*, 31, 187—191. https://doi.org/10.1515/htmp-2011-0148
25. Amelin, A. A. (2023). Titan That Could Be Gold. Why Ukraine is losing millions by refusing to recycle. *Focus,* April 13. URL: https://focus.ua/uk/opinions/560487-titanova-sirovina-yak-zrobiti-shob-ukrayinskij-titan-prinosiv-bilshe-pributku (Last accessed: 20.08.2023).
26. Acumen Research and Consulting. (2023). *3D Printing in Medical Applications Market Size Growing at 16.6% CAGR Set to Reach USD 11 Billion by 2032*. URL: https://www.globenewswire.com/en/news-release/2023/03/27/2634981/0/en/3D-Printing-in-Medical-Applications-Market-Size-Growing-at-16-6-CAGR-Set-to-Reach-USD-11-Billion-By-2032.html (Last accessed: 22.08.2023).
27. Shaanxi North Steel Company. (2019). Military uses of titanium, January 22. URL: https://www.northsteel.com/2019/01/22/military-uses-of-titanium/ (Last accessed: 22.08.2023).
28. Bewlay, B. P., Weimer, M., Kelly, T., Suzuki, A., Subramanian, P. R. (2013). The Science, Technology, and Implementation of TiAl Alloys in Commercial Aircraft Engines. *Mater. Res. Soc. Symp. Proc.,* 1516, 49—58. https://doi.org/10.1557/opl.2013.44

Received 18.09.2023
Revised 20.09.2023
Accepted 20.09.2023

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РОЗВИТОК ВИРОБНИЦТВА МЕТАЛЕВОГО ТИТАНУ В УКРАЇНІ: НОВІ ПЕРСПЕКТИВИ НА ОСНОВІ ВІТЧИЗНЯНИХ НАУКОВИХ РОЗРОБОК

Вступ. Розвиток ресурсного потенціалу України у галузі видобування та поглибленої переробки титанової сировини є однією з важливих складових протидії воєнним загрозам й відновлення національної економіки на новій технологічній базі.

Проблематика. Реалії воєнного часу посилюють важливість використання внутрішніх ресурсів для ревіталізації повного циклу виробництва продукції металевого титану в Україні, що може сприяти інтеграції до глобальних ланцюгів доданої вартості.

Мета. Визначення напрямів розвитку виробництва металевого титану в Україні на основі наявного ресурсного та виробничого потенціалу, світових і вітчизняних наукових розробок.

Матеріали й методи. Використано дані статистичних спостережень Державної служби статистики, Державної геологічної служби США, Всесвітньої організації інтелектуальної власності; застосовано методи системного підходу, економіко-статистичний, розрахунково-конструктивний, графоаналітичний, статистичних порівнянь та групування, а також системно-порівняльний аналіз.

Результати. Ідентифіковано можливості розкриття ресурсного, виробничого та наукового потенціалу для поглибленої переробки металевого титану в Україні. Визначено чинники, що перешкоджають створенню повного циклу його переробки та обґрунтовано напрями відновлення титанової галузі України, а саме побудова нових та/або модернізація виробничих потужностей із переробки титанової сировини на основі вітчизняних наукових розробок.

Висновки. Україна має стратегічний потенціал для виробництва титанових виробів. Створення можливостей для залучення інвестицій, доступу до капіталу та фінансово-економічних інструментів сприятиме реалізації існуючого потенціалу й технологічної модернізації підприємств титанової галузі, що відкриє для України «вікно можливостей» для запуску повного циклу переробки титанової сировини, виробництва титанової продукції з високою доданою вартістю для потреб воєнно-промислового комплексу та інших високотехнологічних галузей.

Ключові слова: металевий титан, ресурсний потенціал, модернізація виробництва, наукові розробки, переробка титану, глобальні ланцюги вартості.