

A. MAZURKIEWICZ*, J. SMOLIK*#

THE INNOVATIVE DIRECTIONS IN DEVELOPMENT AND IMPLEMENTATIONS OF HYBRID TECHNOLOGIES IN SURFACE ENGINEERING

INNOWACYJNE KIERUNKI ROZWOJU I IMPLEMENTACJI TECHNOLOGII HYBRYDOWYCH W INŻYNIERII POWIERZCHNI

The dynamics of the development of modern technology depends, to a great extent, on the possibilities of producing the innovative materials with high functionality parameters, which could be used in modern, highly advanced technological processes. Surface engineering plays a very important role in this area. This is mainly due to the fact that, for many structural materials, the possibilities of classical formation of their properties (e.g., by heat treatment or the selection of the microstructure, chemical and phase composition) have been practically used up. The material and technological achievements in the surface engineering area allow the modification of the properties of the surface layer of tool and machine components. As a result, they may be better suited to work in increasingly difficult and more demanding conditions. The hybrid technologies, combining several different methods of surface treatment in one complex technological process, are the most advanced solutions compared to already known surface engineering methods. In the article, the authors present the possibilities of shaping the functional properties of the surface layer. The authors describe problems associated with the development of the hybrid technology and provide the examples of physical modelling, design, technological development, and the practical application of a hybrid technology. In this work, the authors also identify the areas whose development is needed for more effective transfer of surface engineering innovations to business applications.

Keywords: duplex surface treatment; multilayer coatings; knowledge transfer mechanism

Dynamika rozwoju nowoczesnych technologii, zależy w dużej mierze od możliwości produkcji innowacyjnych materiałów o wysokich parametrach funkcjonalnych, które mogą być stosowane w nowoczesnych, zaawansowanych procesach technologicznych. Inżynieria powierzchni odgrywa bardzo ważną rolę w tej dziedzinie. Wynika to głównie z faktu, że dla wielu materiałów strukturalnych, konwencjonalne możliwości formowania właściwości, na przykład poprzez obróbkę cieplną lub dobór mikrostruktury, składu chemicznego i fazowego, są praktycznie całkowicie wykorzystane. Materiałowe i technologiczne osiągnięcia w dziedzinie inżynierii powierzchni pozwalają na modyfikację właściwości warstwy wierzchniej elementów narzędzi i urządzeń. W rezultacie takie materiały mogą być lepiej dostosowane do pracy w coraz trudniejszych i bardziej wymagających warunkach. Technologie hybrydowe, łączące kilka różnych metod obróbki powierzchni w jednym złożonym procesie technologicznym, należą do najbardziej zaawansowanych rozwiązań w porównaniu do znanych już metod inżynierii powierzchni. W artykule autorzy przedstawiają możliwości kształtowania funkcjonalnych właściwości warstwy wierzchniej. Opisują problemy związane z rozwojem technologii hybrydowej oraz dają przykłady modelowania fizycznego w projektowaniu materiałów, rozwoju technologicznego oraz praktycznego zastosowania technologii hybrydowej. Autorzy identyfikują również obszary, których rozwój jest potrzebny dla bardziej efektywnego transferu innowacji inżynierii powierzchni do zastosowań biznesowych.

1. Introduction

Innovative solutions in surface engineering have been the foundation of intensive technical development in the world. These systems form huge opportunities in generating functional material solutions in surface engineering, which meet the requirements

of many different, usually individualized, industrial applications. The development of surface engineering caused the emergence of many new coating materials (e.g., multicomponent, multilayer, and gradient coatings) [1-3], as well as hybrid layers which are the result of complex technological processes combining different surface treatment methods [4-5]. This new material enabled the

* INSTITUTE FOR SUSTAINABLE TECHNOLOGIES – NATIONAL RESEARCH INSTITUTE, 6/10 PUŁASKIEGO STR., 26-600 RADOM, POLAND

Corresponding author: Jerzy.Smolik@itee.radom.pl

shaping of functional properties of tools and machine components, which are used in the most important areas of industry, (e.g. in high performance production processes, including metal forming in aerospace and automotive industries) to shape functional properties providing a way to the smooth operation of machines in difficult conditions. The complex hybrid processes enabling the manufacture of multilayer structures of a surface layer are the most advanced and most effective direction of surface engineering development to meet the expectations set by the industry. The appropriate selection of the properties of individual components of the multilayer system ensures their mutual interaction. As a result, it creates a very high opportunity in the shaping of the properties of the surface layer of the workpieces, which cannot be obtained by applying standard methods of surface treatment. With respect to the hybrid technology, the process of designing the surface layer properties includes the coating material and the whole “substrate / coating” system [6-7].

2. Hybrid surface engineering technologies – problems and possibilities

The hybrid technology of surface treatment belongs to the group of advanced technology materials [8-9], combining several different methods of surface treatment in a multi-step process (Fig. 1). This creates a very wide ability to configure the hybrid technology. The appropriate selection of properties

of individual components of the system, i.e. structure, chemical composition, and the morphology of the substrate and coating material, provides the synergistic interaction. As a result, formation of the surface layer properties of workpieces is possible, which cannot be obtained by applying the standard methods of the surface treatment. The development of the hybrid manufacturing processes of layers and coatings focuses on the two main research directions, i.e. the development of the hybrid technology implemented with the use of diffusion processes in subsequent stages correlated with plasma processes technology, laser, etc., and the development of the hybrid multi-source technology using different deposition methods in one process.

The hybrid technology using diffusion processes is mainly carried out for the production of the “diffusion layer/PVD coating” hybrid layers of on the high-alloyed tool steels, in order to increase the durability of the tools and machine parts working in difficult conditions. In the shaping of their properties, the reciprocal and synergetic interaction between the diffusion layer and the PVD coating plays a decisive role. The best recognised and the most commonly used in industrial practice is the hybrid layer that consists of a nitride layer and is directly formed on the PVD coating (Fig. 2). The example is the “nitride layer/(Cr/CrN)_{multilayer}” hybrid layer, which can double the durability of dies, [10].

The hybrid technologies using diffusion processes can also be successfully used to shape the functional properties of non-ferrous alloys (e.g., titanium, aluminium, magnesium). An example of the original hybrid technology in this field is

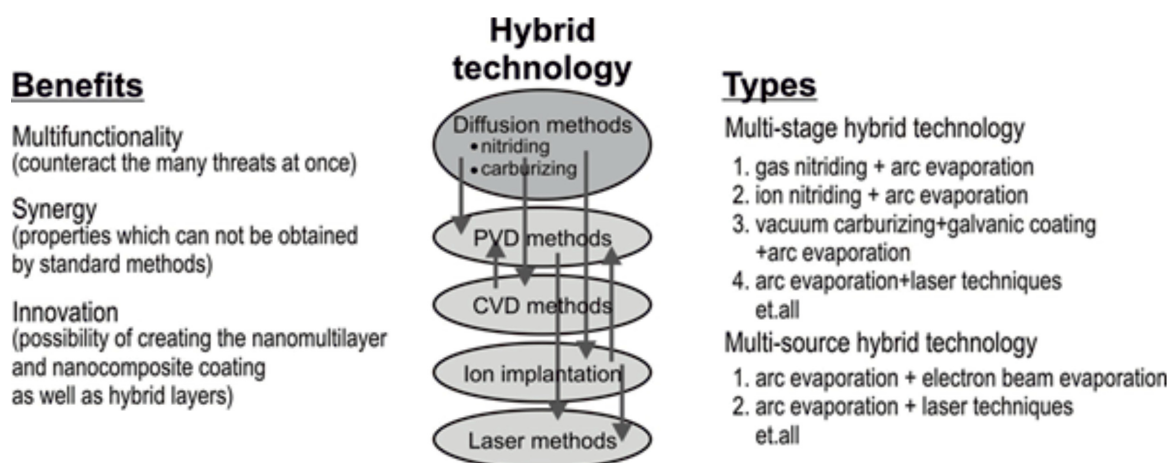


Fig. 1. An outline of potential composition of hybrid surface treatment technologies

the combination of the diffusion processes in powders with the processes of coating deposition by PVD methods. (Fig. 3), shows the $TiAl_{intermetallic} / AlCrTiN$ composite layer formed on the aluminium alloy Ak12 using a hybrid method combining magnetron sputtering, vacuum heating, and the arc evaporation methods in one technological multistage process. The produced composite layer significantly increases the abrasive wear and erosive wear resistance of aluminium alloy Ak12.

The multisource hybrid technologies are very promising solutions for manufacturing composite coatings. An interesting

direction in their use is the hybrid technology, which is a combination of the Arc-PVD and the EB-PVD methods [11], which, depending on the technical configuration, enables the production of a nanomultilayer (Fig. 4a) or nanocomposite coating of chromium carbide Cr_3C_2 in the matrix of Cr-Ni (Fig. 4b) [12]. The $Cr_3C_2 - Cr/Ni$ coatings are characterized by increased erosive wear resistance, and they have been produced almost exclusively by thermal spraying.

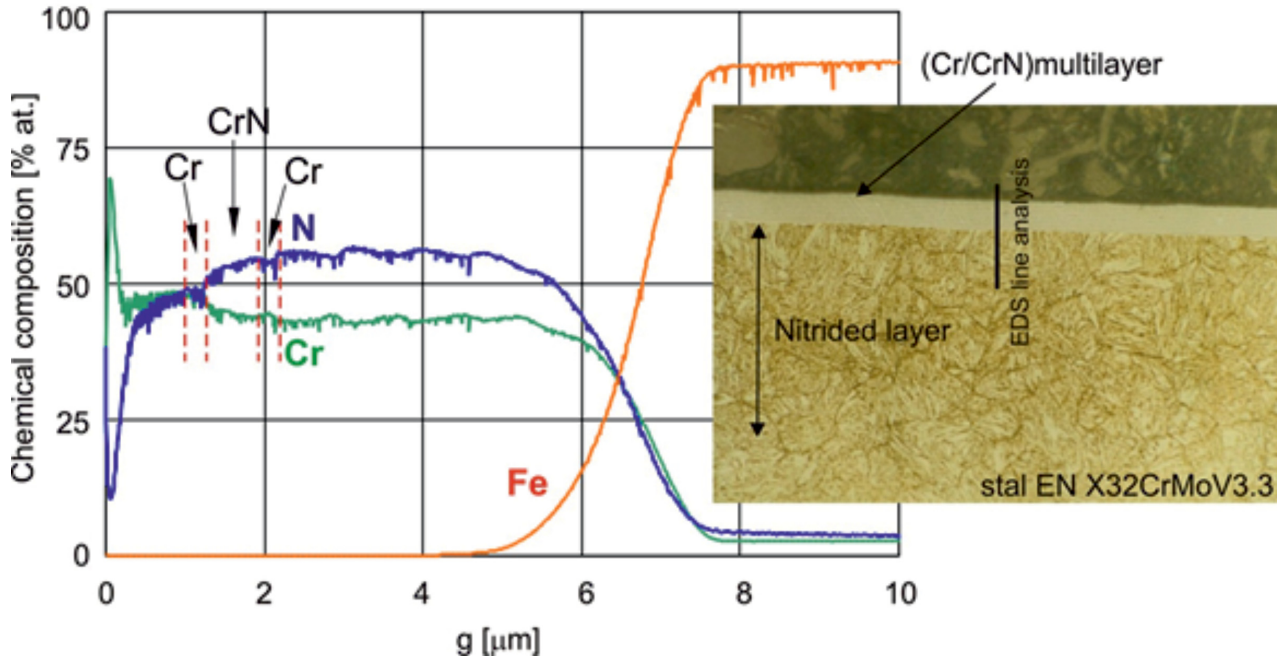


Fig. 2. “Nitrided layer / (Cr/CrN)_{multilayer}” composite layer obtained on the hot working steel EN X32CrMoV3.3

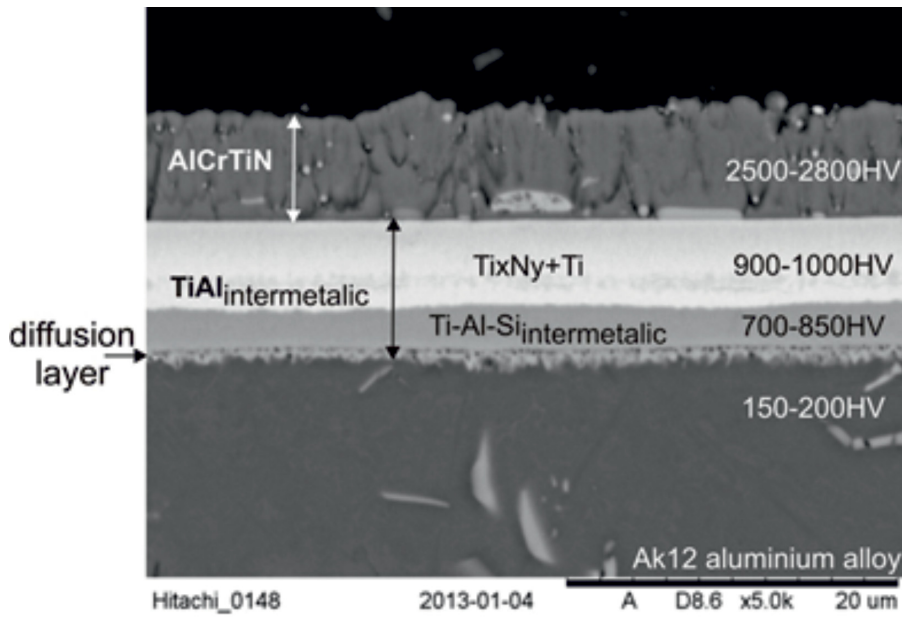


Fig. 3. “TiAl_{intermetallic} / AlCrTiN” composite layer obtained on the Ak12 aluminium alloy

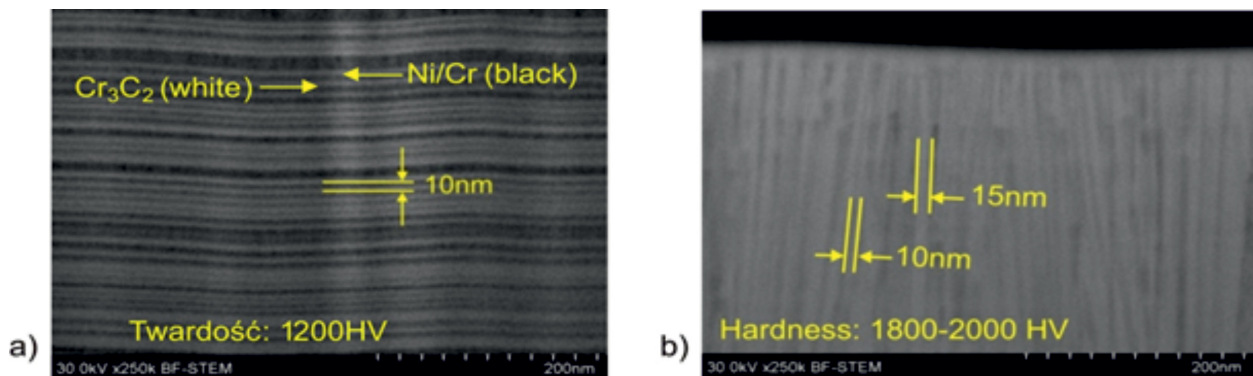


Fig. 4. “Cr₃C₂ – Cr/Ni” functional coating obtained on the Ak12 aluminium alloy by the Arc-EB hybrid method: a) nanomultilayer, b) nanocomposite

3. Examples of development and innovative implementations in surface engineering

3.1. Efficient production processes-increasing the durability of forging dies

The hot forging is a very widely distributed technology of production of elements with a complex shape. The hot forging found a special place in the automotive industry, which is the recipient of more than 57% of all manufactured forgings [13]. Among the most important forged products are forgings dies, whose share in some assortments of production reaches 50 - 80%. As in shown the conducted analysis [14], the production of forgings in the EU in 2005 was nearly 3.5 million tons, while, in 2013, it was more than 5.8 million tons. This confirms the continuous and dynamic development of the hot forging and its importance for the development of the industry.

In the process of hot forging, the tools are subjected to three main factors causing their destruction, i.e. the cyclically variable mechanical loads, the intense thermal shocks, the intensive friction, and erosion [15]. In order to reduce the yield strength, the forged material is heated to a temperature of 1000-1200°C. The cyclically variable nature of loads resulting from the specificity of the forging process causes that the dies are cyclically heated up from the deformable material and then cooled down. It is estimated that the temperature of the die in the surface layer can reach a value of $\approx 900^\circ\text{C}$ [16]. As a result of intensive cyclic

changes of temperature in the surface layer of the material of the die, resulting in thermal stresses and structural stresses, stereotypical conditions to generate a grid of the microcracks were created. This form of destruction of the die material is defined as the destruction of the material due to thermal fatigue. At the same time, the cyclically variable nature of the external mechanical loads operating on the die in the production cycle cause fatigue processes known as the mechanical fatigue of the material. The intensity of destruction increases, due to the mechanical fatigue, as a result of the occurrence of the grid of cracks formed during thermal fatigue, which may additionally increase the stress concentration in the areas of its occurrence. The correlation of thermal fatigue and mechanical fatigue mechanisms means that both mechanisms are considered to be the destruction process of thermo-mechanical fatigue [17]. Due to the large pressure and the movement of the deformable material from the die material, large frictional forces between the die and the forging are generated. Such complex operating conditions means that the material solution of the surface layer dedicated to improving the durability of forging dies must have a multifunctional character, i.e. its needs to increase the fatigue and wear resistance, and it must maintain these properties at temperatures up to 900°C . The material proposed by the authors of the article in this respect is the “nitride layer / $(\text{AlN-CrN-TiN})_{\text{multinano}}$ ” composite layer shown in (Fig. 5a).

The complex structure of the multilayer composite and the synergic interaction of its individual components provide the

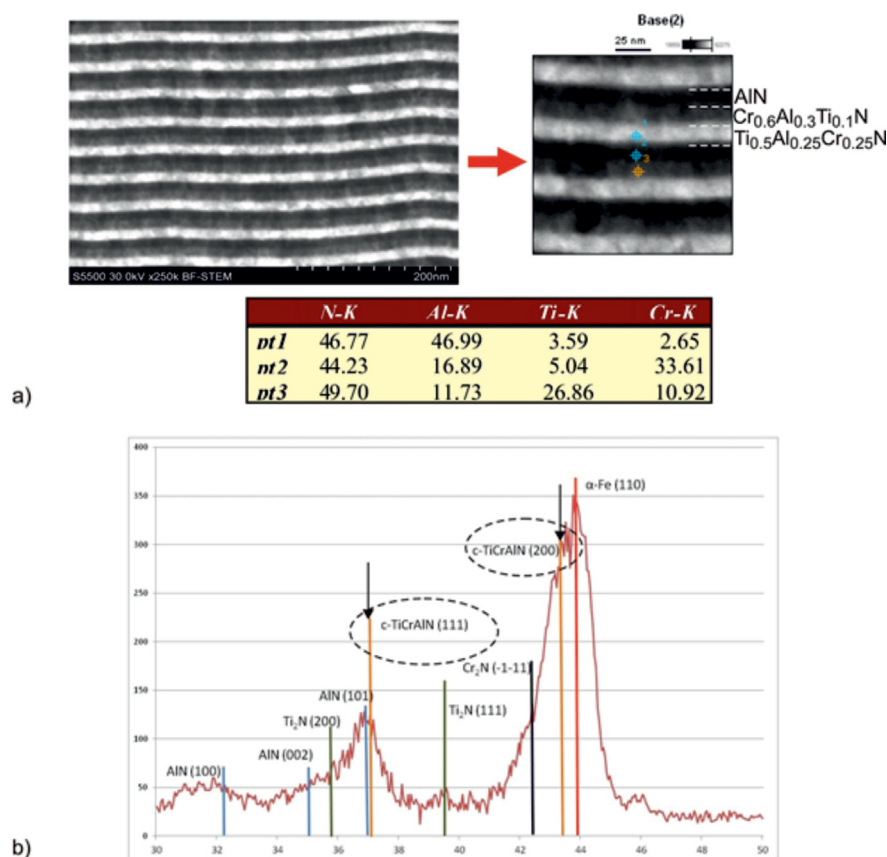


Fig. 5. Functional “nitride layer / $(\text{AlN-CrN-TiN})_{\text{multinano}}$ ” composite layer obtained on the hot working steel EN X32CrMoV3.3: a) microstructure and chemical composition, b) phase composition

multifunctional properties. The nitride layer increases the surface hardness and the plastic deformation resistance of the substrate in the superficial zone. Therefore, it provides a high rigidity of the substrate-coating system and protects the PVD coating against the loss of internal cohesion and adhesion to the substrate. A coherent PVD coating, on the other hand, constitutes the insulating layer of the nitride substrate and reduces the influence of external factors on the process of its destruction. The multilayer structure of the coating effectively prevents the mechanism of the generation and propagation of microcracks, thus increasing the fatigue resistance. Shaping the chemical composition of the $\text{AlN-CrN-TiN}_{\text{multinano}}$ layer enabled the formation of the multimetallic nitrides $\text{AlxCr}_y\text{Ti}_z\text{N}$ [18], which provides high resistance and stability properties (hardness, wear resistance) at temperatures up to 900°C of the coating (Fig. 5b). The multifunctionality of the proposed material solution was confirmed by the service tests conducted in operating conditions in the Bearing Factory in Krasnik. The dies applied in the forging of roller bearings, covered with a composite layer, showed almost four times higher durability, compared with standard dies subjected only to the nitriding process.

Completely different requirements have to be met by the forging tools used in the process of forging brass. In the process of the plastic hot treatment for brass, the forged material is heated to the temperature of $680\text{--}750^\circ\text{C}$. The brass forgings are usually components with complex geometry (casings, water pump impellers, fitting elements of water and gas installations), which are manufactured in one cycle of plastic deformation [19]. This means that the main parameter determining the durability of the dies for brass forging, the efficiency of the forging process, and the quality of the obtained surface is the low coefficient of friction between the forged material and the die. The parameters of

the forging process, particularly the temperature of the process $>600^\circ\text{C}$, practically exclude the use of a material with properties of a solid lubricant based on sulphides, i.e. MoS_2 , WS_2 , NbSe_2 , whose thermal resistances $T_{\text{OC MoS}_2} \approx 200^\circ\text{C}$, $T_{\text{OC WS}_2} < 600^\circ\text{C}$, $T_{\text{OC NbS}_2} \approx 200^\circ\text{C}$ [20]. In addition, the thin hard phase metal oxides like WO_3 , V_2O_5 , and MoO_3 have a similar layered structure, characterized by the presence of slip planes (characteristic of transition metal halides MoS_2 , WS_2 , NbSe_2). These phases, called Magnelli phases, are oxidation products of the metallic components included in the composition of the coating. From among these oxides, using vanadium oxide phase of V_2O_5 and AlVO_4 as a lubricant may be a good solution. Examples are anti-wear coating with a superlattice structure, TiAlN/VN and multicomponent coatings doped with vanadium (TiAlV)N and $(\text{AlCrV})\text{N}$ [21].

Based on the experience in the design of hybrid layers of the nitrided layer / PVD coating types, the authors described the technology of production and the results of tests on material properties of a hybrid layer type “nitride layer / Ti / TiN / $\text{TiAlN}_{\text{gradient}}$ / $(\text{TiAlN/VN})_{\text{multinano}}$ ” obtained on hot working steel EN X32CrMoV3.3. The microstructure of a nitride layer / Ti / TiN / $\text{TiAlN}_{\text{gradient}}$ / $(\text{TiAlN/VN})_{\text{multinano}}$ composite layer is shown in (Figs. 5a, b, c). The thickness of the multilayer coating is about $5\ \mu\text{m}$, and it is characterised by a dense structure free from pores and cracks. The multilayer coatings consist of two zones (Fig. 6a). The first one, located directly on the substrate, is the complex interlayer composed of three different Ti / TiN / $\text{TiAlN}_{\text{gradient}}$ layers with a total thickness of $\approx 650\ \text{nm}$ (Fig. 6b). The second one is the $(\text{TiAlN/VN})_{\text{multinano}}$ coating with total thickness of about $4.5\ \mu\text{m}$, and the thickness of particular nanolayers is about $5\text{--}7\ \text{nm}$ (Fig. 6c). Figure 6d shows the results of tribological tests of samples covered with the examined composite layer and compares them with the results obtained for the samples made of the

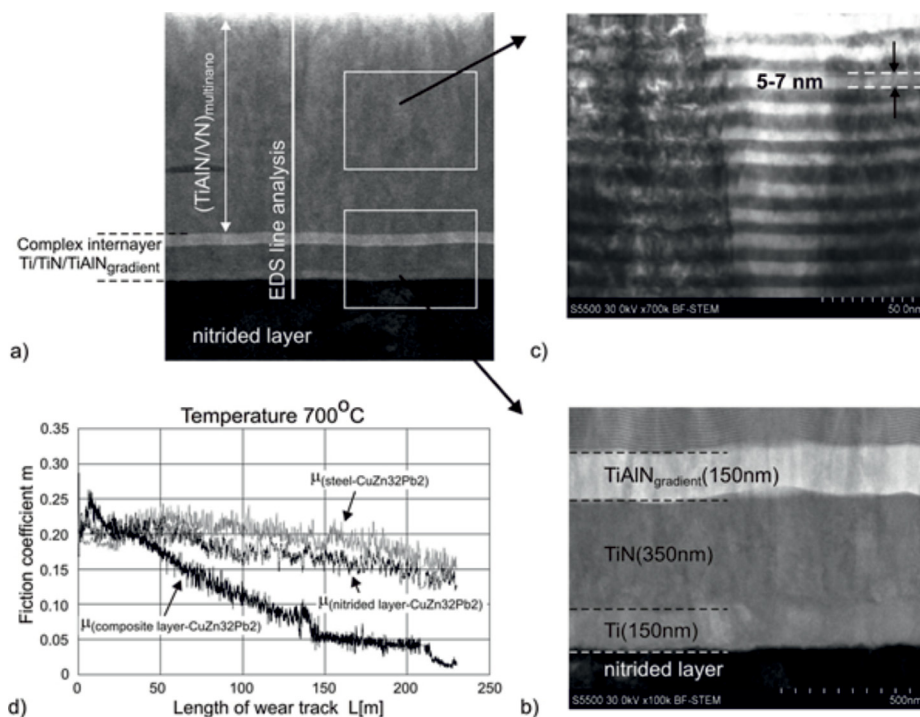


Fig. 6. Functional “nitride layer / Ti/TiN/TiAlN_{gradient}/(TiAlN/VN)_{multinano}” composite layer obtained on the hot working steel EN X32CrMoV3.3

steel EN X32CrMoV3.3 after only the heat treatment process, and after the heat treatment followed by the nitriding process.

The obtained results proved that, at the temperature of 700°C, the friction coefficient of the composite layer systematically decreased during the test from the initial level of 0.20 to the level $\mu_{\text{composite layer}(700)} < 0.05$ at which it remained. At the same temperature, it was significantly lower than for the steel after heat treatment and the steel after plasma nitriding ($\mu_{\text{steel}(700)} \approx \mu_{\text{nitrided layer}(700)} \approx 0.15-0.20$). At the temperature of 700°C, the friction coefficient between the sample with the composite layer and the brass alloy stabilised at the level of $\mu_{\text{CL}(700)} < 0.05$, which is most likely a result of the Magnelli phases V_2O_5 formed at temperatures above 500°C.

3.2. Increasing the erosion resistance of aircraft engine components

An aircraft engine due to its construction and nature of work may be divided into the cold parts responsible for supplying air to the combustion chamber, and the hot parts responsible for combustion of fuel and its transfer in the aircraft (Fig. 7). The working conditions of different parts of the aircraft engine determine the main mechanisms of destruction occurring in those elements. The main mechanism of the destruction of the elements in the hot part is high-temperature corrosion [22]. Issues related to the use of surface engineering to enhance the stability of the components of the hot section of the engine are quite well known and concern the use of *TBC – Thermal Barrier Coating* [23] products based on zirconium ceramics. The main mechanism of the destruction of elements in the cold section of

the aircraft engine is erosive wear resulting from the presence of different particles (sand, ice) in the air supplied to the engine.

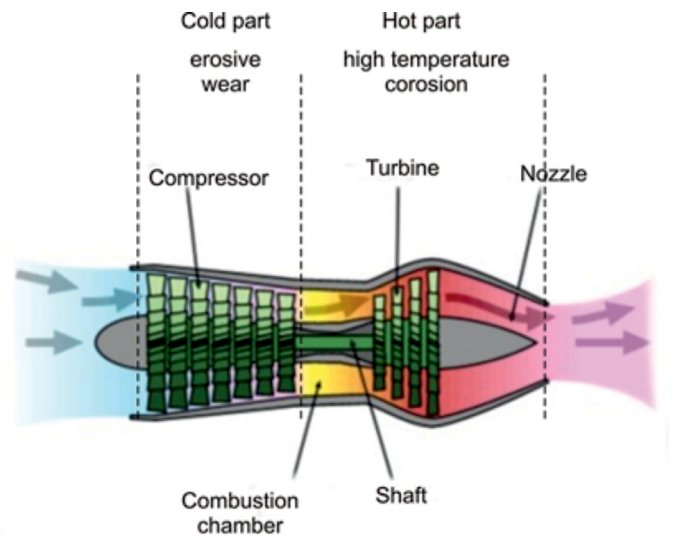


Fig. 7. Scheme of the aircraft engine

The working conditions of hot engine components are stable and do not depend on the climatic and weather conditions, while the cold section, and thus the erosion process parameters, depend significantly on the conditions under which the aircraft operates. Therefore, the process of designing the material solutions of surface layers designed to increase the erosion resistance of compressor components must be preceded by an analysis of the environmental conditions in which the engine be operate. The (TiN-ZrN)multinano / TiN multilayer

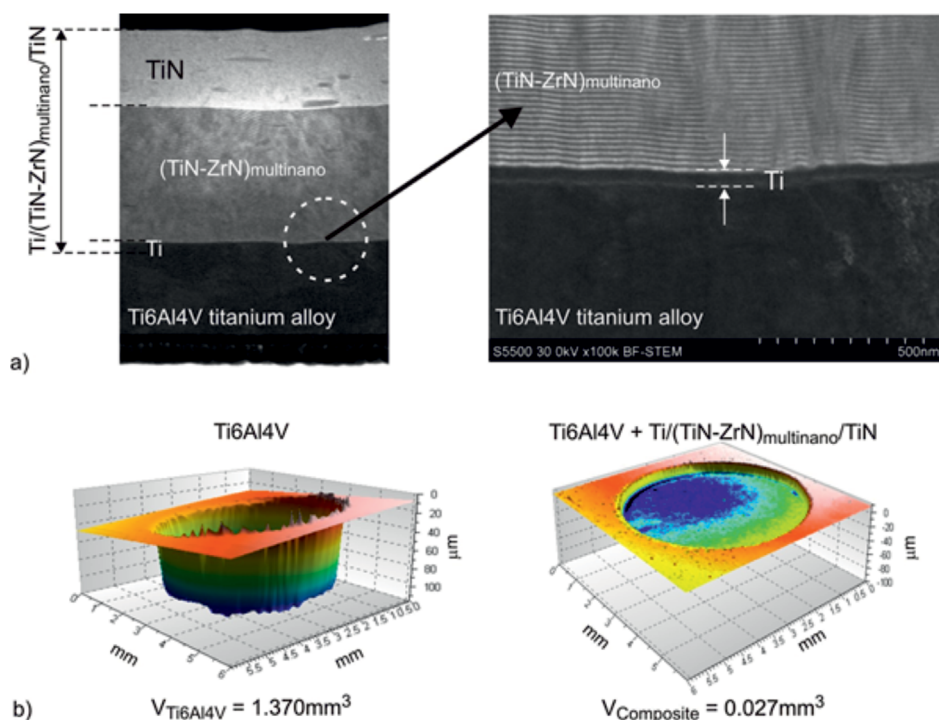


Fig. 8. The functional “Ti / (TiN-ZrN)_{multinano} / TiN” multilayer coating obtained on the hot titanium Allo6y Ti6Al4V by a). arc evaporation method, and b). results of erosion tests

coating (Fig. 8a) is dedicated to increase the erosion resistance of compressor components made of titanium alloy Ti6Al4V for helicopter engines operating in desert conditions. The proposed material solution enabled the erosion resistance of compressor blades made of titanium alloy Ti6Al4V to increase by nearly five times (Fig. 8b).

The study of this coating was carried out using erosion testing equipment specially designed, according to the concept with the participation of the authors of the article [24] (Fig. 9). The instrumentation enables the executing of erosive wear research in a wide range of parameters, i.e. the temperature of the sample 25°C-600°C, the temperature of the abrasive particles from 25°C to 450°C, and in the wide range of the speed of the abrasive particles from 10 m/s to 130 m/s. The angle of the sample relative to the abrasive particles can be adjusted between 0°C-55°C.

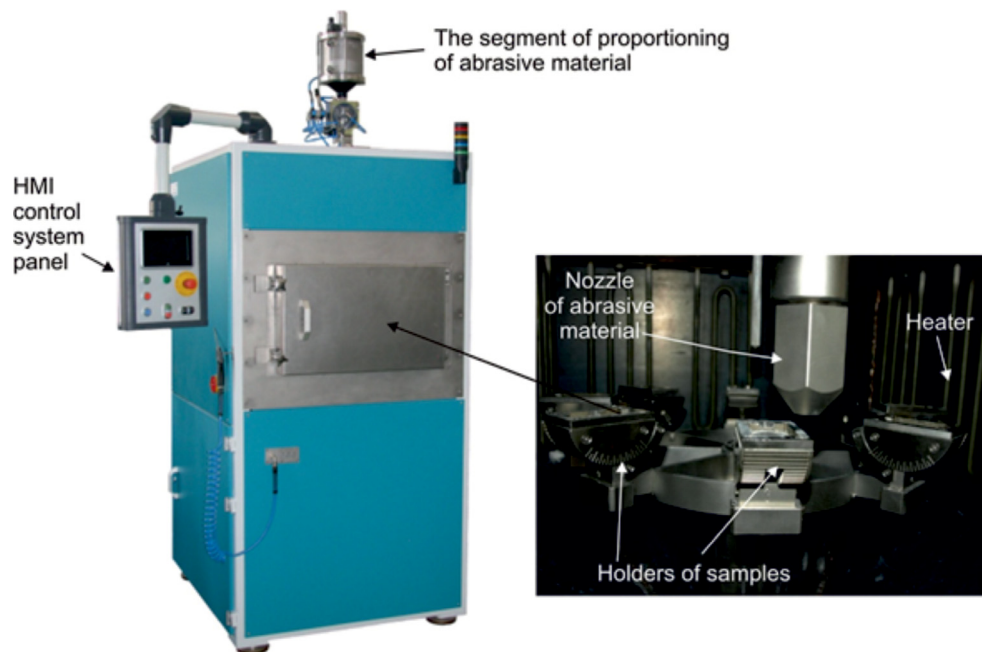


Fig. 9. The universal test equipment to carry out research on erosion processes designed and produced in ITeE-PIB in Radom

4.1. Devices and systems for implementation of hybrid surface engineering technologies

The analysis of technological application in the hybrid technology of surface engineering indicated that the basic factor ensuring the effectiveness of activities in this area are the technical conditions for the industrial implementation of the developed technologies. Primarily, one should consider the technological equipment and components for the implementation of the modern technology of surface treatment and the control systems of technological processes. The advancement of the construction equipment determines the possibilities in controlling the parameters of the technological process. Different surface treatments are often carried out for very different technological parameters (pressure, temperature, etc.). They use different ways of composing the atmosphere of the process (gas media, liquid media), and often require different power supply and control systems.

4. The necessary support areas for surface engineering innovation

The processes of the design and manufacture of hybrid layers require deep scientific knowledge in the area of materials science, in particular, the impact of the individual component layers and their structure on the properties of the composite, as well as extensive technological experience including, among others, the knowledge of the impact of the various process parameters on the properties of the obtained films and coatings. However, the equivalent factor in determining the development of innovative, hybrid surface engineering technologies, and above all, the ability to practical manufacture the complex surface layer material solutions, are the technical capabilities and resources of unique materials.

Therefore, the implementation of hybrid technologies and their effective application in the economy requires multifunctional and often unique technological devices that allow the implementation of innovative surface treatment methods, in accordance with the required technological parameters, in one process chamber. An original and multifunctional technological device adapted to perform advanced hybrid technologies, developed and manufactured at the Institute for Sustainable Technologies – National Research Institute in Radom, is shown in (Fig. 10). The device is equipped with a vacuum chamber ensuring the process zone in the cylindrical shape and the following dimensions: diameter $\phi = 500$ mm, height $h = 800$ mm. The efficient turbo molecular pump system ensures stable operation in a wide range of pressure and airflow values in the process chamber. The use of a turbo molecular pump also provides the high purity of the process atmosphere, which is not possible in the case of oil diffusion pumps.

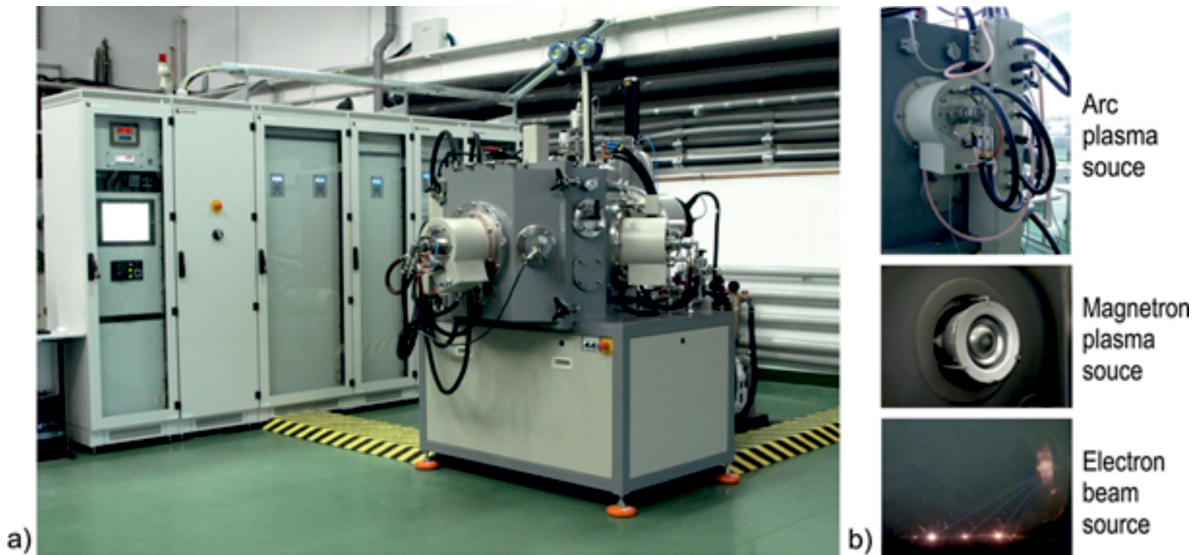


Fig. 10. Technological device enabling the practical implementation of hybrid surface treatment technologies produced by Institute for Sustainable Technologies in Radom, Poland: a) device, b) different plasma sources (arc, magnetron, electron beam)

The process atmosphere is created using a 4-channel gas dosing system, allowing both pressure stability (while keeping relative proportions of the individual gases), and the stability of the inert gas pressure at a constant flow rate of three reactive gases. The device is equipped with various plasma sources, including a magnetron plasma source, an arc plasma source, and an electron beam plasma source, and a specially designed power systems. A device configured in this way allows the implementation of different methods of surface engineering, both in multistep and multisource processes, in which different

surface engineering methods are carried out at the same time.

Specialized technological components play an important role in ensuring the possibility of the implementation of modern hybrid technology. The modern systems of rotating and positioning the covered elements in the precisely defined area of the process chamber and in a precisely defined time ensure the production of multilayer coatings, especially nanomultilayer coatings. (Fig. 11) shows the different examples of a rotation system for rotating the components relative to both the vertical and horizontal axis of the process chamber.

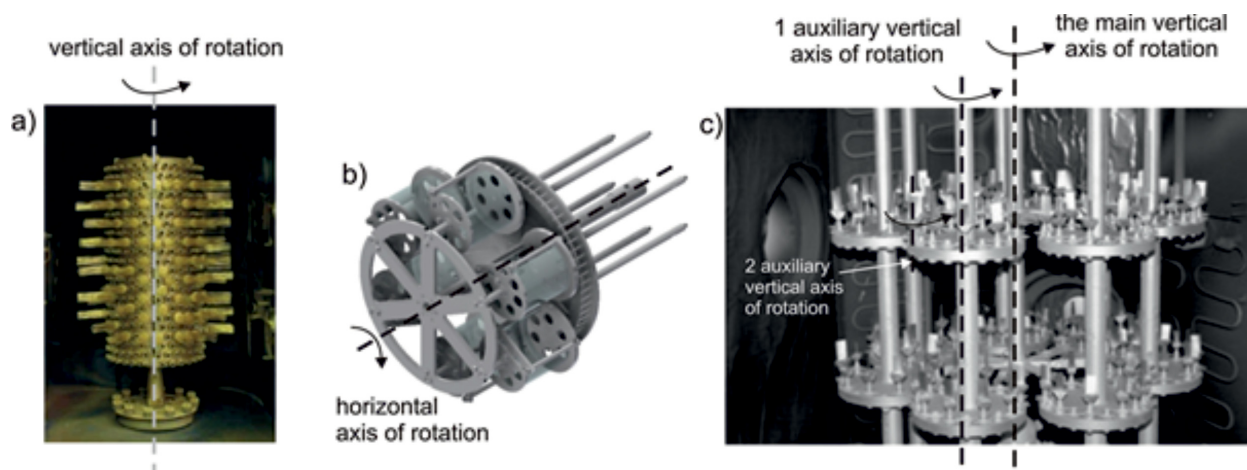


Fig. 11. Various examples of rotation systems designed in ITeE-PIB in Radom: a) according with the vertical axis, b) according with the horizontal axis, c) planetary system with three different vertical rotation axes

The modern technological developments often require very advanced and original design studies based on material knowledge and technological experience. An example is the original design of the multi-position modular crucible, allowing the production of the multilayer coatings in which the individual component layers are materials that require different parameters

of evaporation by the electron beam evaporation method. The concept of the multi-position modular crucible was created by splitting the standard crucible into four modules, according to the division of materials into four groups carried out over high thermal conductivity materials, low thermal conductivity materials, refractory materials, and sublimating materials [25]. In

order to evaporate materials with a low coefficient of thermal conductivity (e.g., Ti, Al_2O_3), where intense heat dissipation from the walls of the crucible is required, a typical copper crucible directly cooled with water was designed. Because of the high thermal conductivity of copper (401 W/(mK)), the heat is effectively removed from the melted charge heated to the temperature of 1700-1800°C. This enables carrying out long-term deposition processes without the threat of crucible overheating. For the materials with high coefficient of thermal conductivity (e.g., Al, Cu) and low melting point that require a crucible with low thermal conductivity, a crucible made of ceramic material (ZrO_2 , BN) was designed. For the infusible materials (e.g. W, Mo) with high thermal conductivity and high melting point (2600-3400°C) that require a crucible with limited thermal conductivity, a graphite crucible with the inner surface of the walls coated with ZrO_2 ceramic coating with a thickness of ~150 μm was designed. The low coefficient of thermal conductivity of ZrO_2 allows the crucible to work at temperatures

above 3500°C. For the sublimating materials (e.g., Cr) that require the use of crucible allowing continuous movement of the evaporated areas of the material in the electron beam operation area, a rotary water-cooled crucible was designed. The introduction of crucible rotation allows even evaporation of the material from the entire surface of the charge. The crucible with four different positions adapted to the evaporation of materials with different thermal properties and mounted in the vacuum chamber is shown in (Fig. 12a). The effect of the application of a multi-position modular crucible for the evaporation of materials with different thermal properties, *i.e.* aluminium – as a material with high coefficient of thermal conductivity, titanium – as a material with low coefficient of thermal conductivity, and tungsten – as material with high melting point and chromium – as a sublimating material is shown in (Fig. 12b). A thicker than 25 μm Ti-W-Al-Cr multilayer coating, with good cohesion between particular layers, was obtained in one technological electron beam evaporation process.

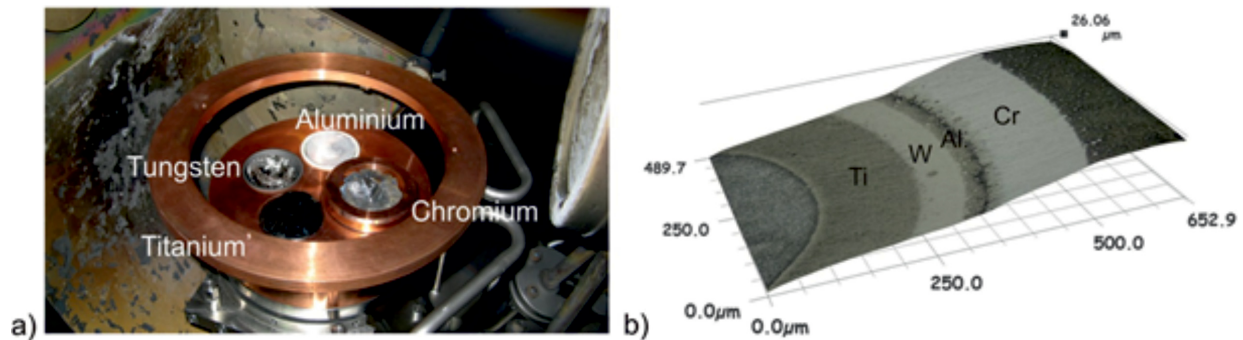


Fig. 12. Multi-position modular crucible designed in ITeE-PIB in Radom: (a) mounted in the vacuum chamber, (b) Ti-W-Al-Cr multilayer coating obtained in one technological electron beam evaporation process

The main directions of current activities in the construction of unique technological equipment for hybrid technologies of surface engineering include the development of a number of devices to implement the plasma surface treatment processes in an on-line system. In commercial practice, equipment enabling the implementation of plasma surface treatment processes in an on-line system, including hybrid technologies, significantly improve the economic effectiveness and efficiency of the process.

4.2. Exploitation materials for implementation of hybrid surface engineering technologies

The production of the hybrid layers with specific, well-defined operating properties requires the use of sources of the vapour with a specific chemical composition and structure. This primarily applies to layers and coatings designed based on ceramic materials such as Al_2O_3 or ZrO_2 thermal barrier layer TBC, as well as coatings with complex chemically defined, for example, multiple coatings, e.g. AlCrTiN , $\text{AlCrTiN}/\text{Si}_3\text{N}_4$, as well as coatings based on quasi-crystalline Al-Cu-Fe, Al-Cu-Co alloys.

The experience of the authors of the article indicates that the method of manufacture, the homogeneity of the chemical composition, and the purity and porosity, etc., of the targeted operating materials can significantly influence the microstructure of the coatings produced. An example might be a microstructure of a CrAlN coating formed by arc-evaporation using targets with the same material composition and obtained by means of two different methods, *i.e.* by low-pressure casting and sintering of powders, as shown in (Fig. 13).

A very large proportion of a phase of microdrops with a dominant share of Al in a coating produced using a cathode obtained from the sintering of powders (Fig. 12b) changes the coating properties, including both mechanical properties (fracture toughness), thermal properties (heat resistance, thermal conductivity), and tribological properties (coefficient of friction, the abrasive and erosive wear resistance).

The operating materials for the implementation of modern hybrid surface engineering technologies should include targets for producing coatings of the arc evaporation and sputtering method, as well as materials for the implementation of electron beam evaporation processes. The expectations on the surface

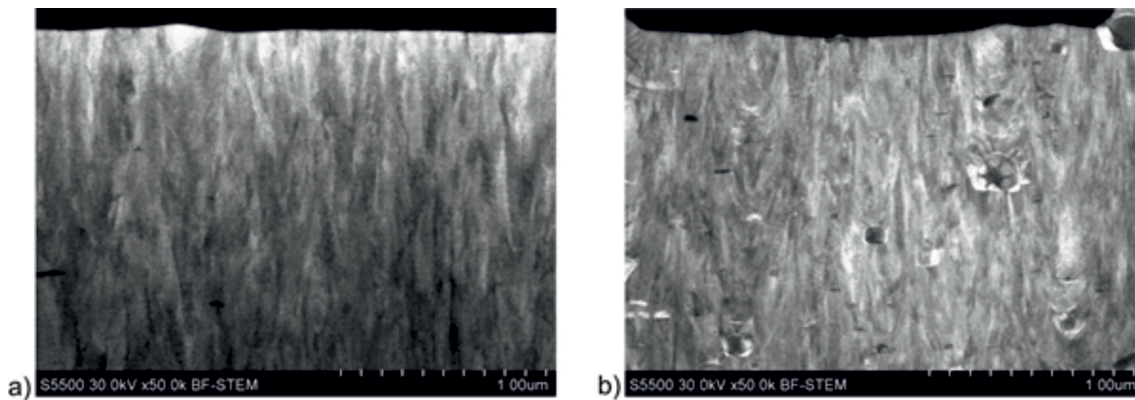


Fig. 13. The microstructure of CrAlN coating formed by arc-evaporation of targets with the same chemical composition made using two different methods: a) by casting, b) by low-pressure sintering of powders

engineering technologists in this field include the chemical composition and structure of these materials, while providing for proper shape and weight. The analysis of information concerning the formation of the chemical composition and phase structure vapour sources used in surface treatment technologies indicates that the activities in this area are mainly focused around three methods [26-28], i.e. casting methods, spark plasma sintering, and selective laser melting.

A special group of consumables increasingly used in the implementation of modern surface engineering technologies are nanomaterials, including the targets of the nanometric grain size in particular. This applies especially targets at low temperature evaporation like aluminium, which is an essential ingredient in coatings with improved heat resistance (CrAlN, TiCrAlN).

The innovative direction in the development of operating materials for the purpose of surface engineering is the use of na-

nomaterials [29]. The examples are aluminium-based targets for arc plasma sources. In the case of Al, it is possible to grind grains to about 0.6-0.8 microns and produce in sub-grains with the size of 100-300 nm. The grains are ground under shear deformation, usually with the participation of high pressure. These deformations can be achieved in various ways, e.g. pressing, twisting, rolling, and bending. These processes are called SPD – Severe Plastic Deformation. Among common SPD techniques, the best results in the production of nanomaterials are obtained for pressing in an angular channel ECAP – Equal Channel Angular Pressing. The cooperation of the ITeE-PIB in Radom and the Department of Materials Science and Engineering at the Warsaw University of Technology, using the angular pressing ECAP, led to the development of an original method for the production of targets from ultrafine grained aluminium, designed for arc plasma sources (Fig. 14).

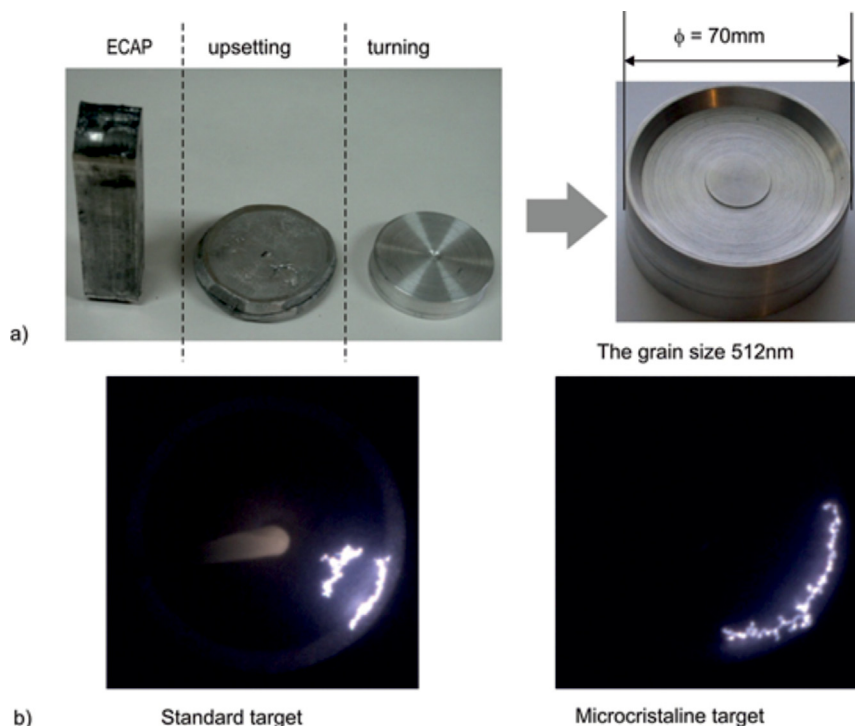


Fig. 14. The diagram of the model of the manufacturing method of ultra (a) fine grained aluminium targets, designed for arc plasma sources, (b) differences in the location of arc evaporation at the cathode

5. Summary

The development of surface engineering is very dynamic and includes incremental technologies, characterized by a high level of technological readiness, and emerging technologies, considered to be a priority for future economic growth. Incremental technology development is aimed at gradual improvement of existing solutions, as well as expanding the possibilities of their application in the economy. Research and experimental development on incremental technologies focus mainly on shaping the characteristics of thin films and coatings designed to improve the mechanical, tribological, and corrosion properties of tools and machine parts working in demanding conditions.

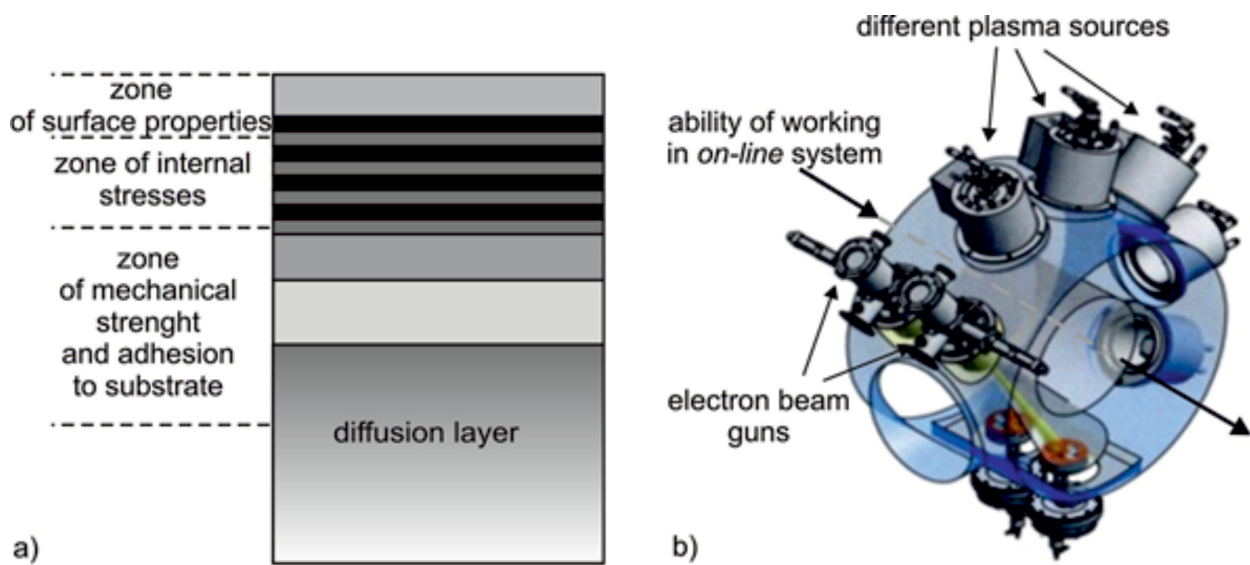


Fig. 15. The main development areas in hybrid surface engineering technologies a) designing of multifunctional coatings, b) modern, multifunction vacuum chambers

The practical use of the advanced surface engineering technologies requires a coherent development of different research areas, including the following:

- Basic knowledge in the field of materials engineering design for films and coatings with functional properties;
- The mathematical modelling ability of functional layers corresponding to the technological needs using expert systems and specialized knowledge bases;
- The technological knowledge directed at the development of hybrid technologies combining various methods of surface engineering;
- The ability to design and manufacture operating materials including nanomaterials;
- The technical infrastructure supporting the implementation of the developed technologies;
- The organizational systems responsible for the transfer of innovative solutions to the industry.

Only the concurrent development of these areas of knowledge, taking into account the mutual research and application needs provides a creative development of multifunctional hybrid

technologies of surface engineering based on the latest achievements of surface engineering, which are the hybrid surface treatment technologies, enables one to shape physical and chemical properties of produced films and coatings. The emerging technologies are created based on innovative materials and the accompanying technological studies, enabling the practical production of functional materials. The future of this area of work is the creation of a technological foundation for the production of the material solutions of surface layers with specific properties (Fig. 15a), as well as the technical conditions for their practical implementation, including specialized and multifunctional technological devices (Fig. 15b).

technologies of surface engineering based on a robust scientific foundation and analysis of the physical phenomena associated with their formation, and the effective transfer of the developed innovative solutions to industrial practice.

Acknowledgments

Scientific work executed within the Strategic Programme “Innovative Systems of Technical Support for Sustainable Development of Economy” within “Innovative Economy Operational Programme.”

REFERENCES

- [1] B. Major, W. Mróz, T. Wierchoń, R. Ebner, Proc.SPIE Laser Technology VII: Application of Lasers **5229**, 163-172 (2003).
- [2] L. Major, J. Morgiel, J.M. Lackner, W. Waldhauser, R. Ebner, L.C. Nistor, G. van Tandeloo, B. Major, Surface and Coating Technology, Elsevier **200**, 6190-6195 (2006).

- [3] J. Smolik, K. Zdunek, *Surface and Coatings Technology* **116-119**, 398-403(1999).
- [4] M. Gołębiewski, G. Krużel, R. Major, W. Mróz, T. Wierzchoń, B. Major, *Materials Chemistry and Physics* **81**, 315-318 (2002).
- [5] J. Smolik, M. Gulde, J. Walkowicz, J. Suchanek, *Surface and Coatings Technology* **180-181**, 506 (2004).
- [6] R. Priestner, D.M. Priestner, "Surface Engineering & Heat Treatment – Past, Present and Future" Edited by P.H. Morton, Published by The Institute of Metals, 1 Carlton House Terrace, London SW1Y 5DB, ISBN:0-901716-01-4, pp. 134 (2010).
- [7] J. Walkowicz, J. Smolik, K. Miernik, *Surface and Coatings Technology* **116-119**, 361-366(1999).
- [8] J. D'Haen, C. Quaeqhaegens, L.M. Stals, M. Van Stappen, *Surface and Coatings Technology* **61**, 194(1993).
- [9] B. Major, T. Wierzchoń, M. Gołębiewski, *J. Mat. Sci. Letters* **21**, 1289-1292(2002).
- [10] J. Smolik, *Archives of Metallurgy and Materials* **57** (3), 657 (2012).
- [11] L. Major, J. Morgiel, J.M. Lackner, M. Kot, M. Szczerba, B. Major, *Advances Engineering Materials*, Wiley-VCH **7**, 617-621(2008).
- [12] A. Mazurkiewicz, J. Smolik, *Materials Science Forum* **674**, 1-9 (2011).
- [13] H. Kubotera, *Journal of Materials Processing Technology* **59**, 213 (1996).
- [14] www.euroforge.org
- [15] O. Barrau, C. Boher, R. Gras, F. Rezai-Aria, *Wear* **255**, 1444 (2003).
- [16] M. Terčelj, R. Turk, M. Knap, *Applied Thermal Engineering* **23**, 113 (2003).
- [17] J. Smolik, A. Mazurkiewicz, *International Heat Treatment and Surface Engineering* **5**, 175 (2011).
- [18] H. Hasegawa, T. Yamamoto, T. Suzuki, K. Yamamoto, *Surface and Coatings Technology* **8**, 2864 (2006).
- [19] Kchaou M., Elleuch R., Desplanques Y., Boidin X., Degallaix G., *Engineering Failure Analysis* **17**, 403-415 (2010).
- [20] Carmalt Claire., J. Manning, Troy D., Parkin, Ivan P., Peters, Emily S. and Hector, Andrew L., *Thin Solid Films* **469-470**, 495-499 (2004).
- [21] Mayrhofer P.H., Hovsepian P.Eh., Mitterer C., Münz W.-D, *Surface and Coatings Technology* **177-178**, 341-347 (2004).
- [22] B.A. Pint, J.A. Haynes, Y.Zhang, *Surface and Coatings Technology* **25**, 1236 (2010).
- [23] Lau Hendrik, *Surface and Coatings Technology* **235**, 121 (2013).
- [24] W. Mizak, A. Mazurkiewicz, J. Smolik, A. Zbrowski, *Maintenance and Reliability* **16**, 4, 559 (2014).
- [25] A. Mazurkiewicz, J. Smolik, A. Zbrowski, J. Kacprzyńska, *Archives of Civil and Mechanical Engineering* **14**, 250-254 (2014).
- [26] Shigeru Ito, Naoyuki Umehara, Hidenori Takata, Takashi Furii, *Solid State Ionics* **172**, 403 (2004).
- [27] Jinsheng Hong, Lian Gao, S.D.D.L. Torre, Hiroki Miyamoto, Key Miyamoto, *Materials Letters* **43**, 27 (2000).
- [28] Xinghong Hang, Qiang Qu, Jiecai Han, Wenbo Han, Changqing Hong, *Scripta Materialia* **59**, 753 (2008).
- [29] A. Mazurkiewicz, *Nanonauki i nanotechnologie – Stan i perspektywy rozwoju, ITeE-PIB w Radomiu 2007*, ISBN 978-83-7204-580-5 (2007).