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Advanced materials and protective coatings in aero-engines application

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ABSTRACT

Purpose: The following article demonstrates the characteristics of the materials applied as parts of aircraft engine turbines and the stationary gas turbines. The principal technologies for manufacturing the heat resistant coatings and the erosion and corrosion resistant coatings were characterized. Sample applications for the aforementioned coatings are presented: on turbine blades, compressor blades and on parts of combustion chambers of aircraft engines.

Design/methodology/approach: The nickel-based alloys were characterized. The following methods of depositing diffusion aluminide coatings were described: pack cementation, out of pack and CVD (chemical vapour deposition). The properties of thermal barrier coatings obtained by thermal spraying and physical vapour deposition (PVD) were presented.

Findings: : The structures of aluminide and platinum modified aluminide coatings, which displayed higher heat resistance during the cyclic oxidation test, were presented. The structure of TBC coatings was described as well. During aircraft engine tests, the compressor blades with multilayer type Cr/CrN coatings exhibited higher wear resistance than the coatings covered with Ti/TiN.

Research limitations/implications: The aluminide coatings were deposited on nickel-based superalloys, which are typically used to manufacture turbine blades for aircraft engines. The multilayer nitride coatings were produced by Arc-PVD method.

Practical implications: All the described technologies and coatings find applications on parts of aircraft engines.

Originality/value: The presented advanced technologies of manufacturing protective coatings on the parts of aircraft engines were developed by the authors of the following study as parts of their planned scientific research, research projects, and purpose projects.

Keywords: Thin & thick coatings; Aluminide coatings; TBCs; Multilayer coatings

1. Introduction

The gas turbine engines operate in one of the harshest environments, which enforces the continuous development of the applied materials. Aircraft engine parts are exposed to severe mechanical loads, high temperature, as well as corrosion and erosion media. Since the early stages of modern engine construction, their producers have been applying protective coating systems in order to enhance their durability and to maximize the exploitation of the properties of the used materials [1]. Modern engine constructions together with the technological advancement lead to the evolution of new coating types and to the improvement of the formerly used coatings. Fig. 1 presents applications of a variety of protective coatings for the parts of an aircraft engine. In the front part of the engine, the so-called cold section, including the fan and the compressor, the abrasion and erosion resistant coatings and seals are typically employed. In modern engines, such cold section parts as fan blades, compressor blades and impellers are made of composites, titanium-aluminium alloys, titanium and heat resistant steels. However, in the hot section of the engine, which includes the combustion chamber area and the turbine, the thermal barrier coatings (TBCs) and high-temperature seal coatings are used. The hot operating temperature of the parts demands the application of superalloys, mainly nickel based alloys. The turbine blades, initially manufactured from plastically worked, and after that, from cast materials, are produced by either directional or monocrystalline solidification at present. Simultaneously to the development of the turbine blade alloys, a progress in the heat resistant coating and thermal barrier coating technologies occurred. The present article aims to characterize the currently applied nickel-based alloys and to present the authors' own research on the abrasion and erosion resistant coatings, diffusion aluminide coatings and thermal barrier coatings.

2. Material development

The developmental tendencies in obtaining high performance of gas turbines are chiefly connected with an increase in the engine's capacity, its efficiency, lifetime, reliability and a decrease in the fuel consumption. These may be achieved by applying high temperature inlet gases, the pressure increase, using more durable materials and enhancing the method of part manufacture. The main focus is on improving the comprehension of the construction demands and the possibilities of protecting the first stage turbine blades and vanes, together with the cooling systems, indispensable for their proper functioning. Within the last decades, a significant progress has occurred in the improvement of the mechanical properties and the structural stability of nickel and cobalt alloys applied in turbine manufacture. So far, however, the increase in the high temperature creep resistance of these materials was achieved at the expense of their oxidation and hot corrosion resistance. Those materials need to be resistant to the high temperature of the gas stream, which may have a strong oxidizing, corroding or eroding impact. The influence of the destructive environment might be incredibly complex, depending on the engine construction, its working cycle, the used fuel and its operation site. At present, the feasible temperature of inlet gases exceeds the capabilities of the most advanced alloys and the most developed engine part construction technologies. Fig. 2 shows the current state of alloy development as compared to the gas temperature feasibility [2].

For the last 25 years, the technological development and the chemical content evolution co-occurred with the progress in the blade cooling systems. The complicated cooling systems are easier to realize in larger blades; in small engines, nevertheless, the material enhancement and the technological development, as well as the improvement of protective coatings would be desirable.

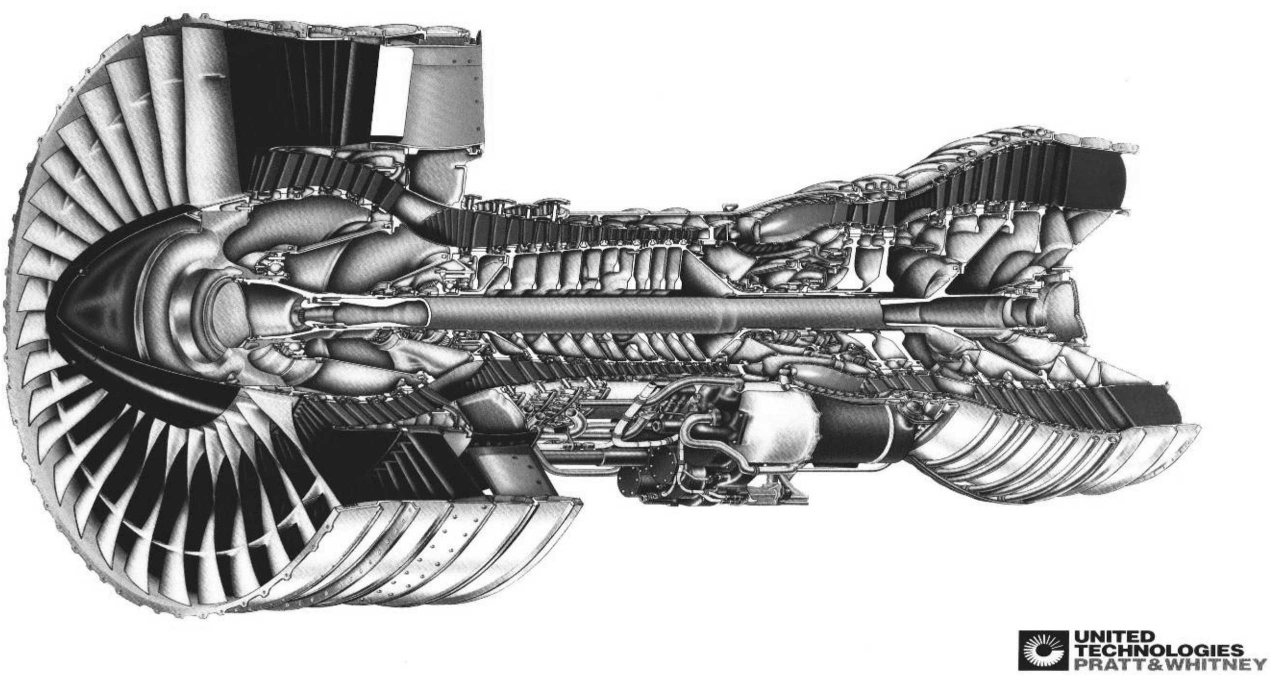

Fig. 1. The application of protective coatings on the parts of the aircraft engine

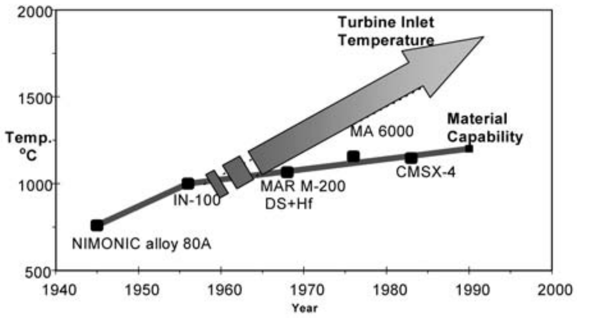

Fig. 2. The present condition of alloy development as compared to the gas temperature feasibility [2]

2.1. Nickel base superalloys

Fig. 3 presents the evolution in the chemical composition of the superalloys, as well as the methods of their obtainment over the last 50 years, together with the approximate dates of introducing their production [2]. As shown in the figure, a number of principal trends could be differentiated within the technological development. During the previous stage, when the alloys were cast in the open furnaces, the amount of the strengthening phase γ' was comparatively small. This restriction, however, was eliminated when vacuum melting was introduced in the 1950s. This improved both the quality and the properties of the alloys substantially, mainly due to the increase in the amount of the strengthening phase γ' and the stricter control of the content, thus proving to be the major breakthrough in the introduction of casting alloys (Alloy 713C, IN-100, IN-738LC) [2]. As the vacuum melting technology developed, a tendency to increase the amount of γ' phase and to decrease the chromium content appeared, with the object of obtaining the proper creep resistance [3]. By contrast, the alloys applied for industrial turbine blades were developed so as to gain the highest hot corrosion resistance, while preserving average mechanical properties [4]. This direction seems to have dominated for turbines using fuel with a high content of sulphur, whose compounds accelerated the corrosion process. IN 738 and IN 939, which contained 16 and 22.5 % of chromium, belonged to this group.

As the directional solidification technology for the aircraft engine turbines developed, certain alloys, e.g. Mar-M 200, which had previously been cast, were obtained by directional solidification [3]. The cracking of casts on the grain boundaries enforced hafnium modification of the alloys, with the view of enhancing their plasticity [2]. Similar technologies have been introduced into the parts of stationary turbines: for instance GTD 111 alloy, initially cast traditionally, is currently directionally solidified. Other alloys have also been introduced into this technology: IN 792 and IN 939 [4]. It is therefore apparent that the enhancement of superalloys properties has chiefly been achieved by means of influencing their structure through modification and technological development. The last 15 years, in particular, marked a rapid progress in the alloy structure forming opportunities, which seems to be the result of directional solidification and single crystals production.

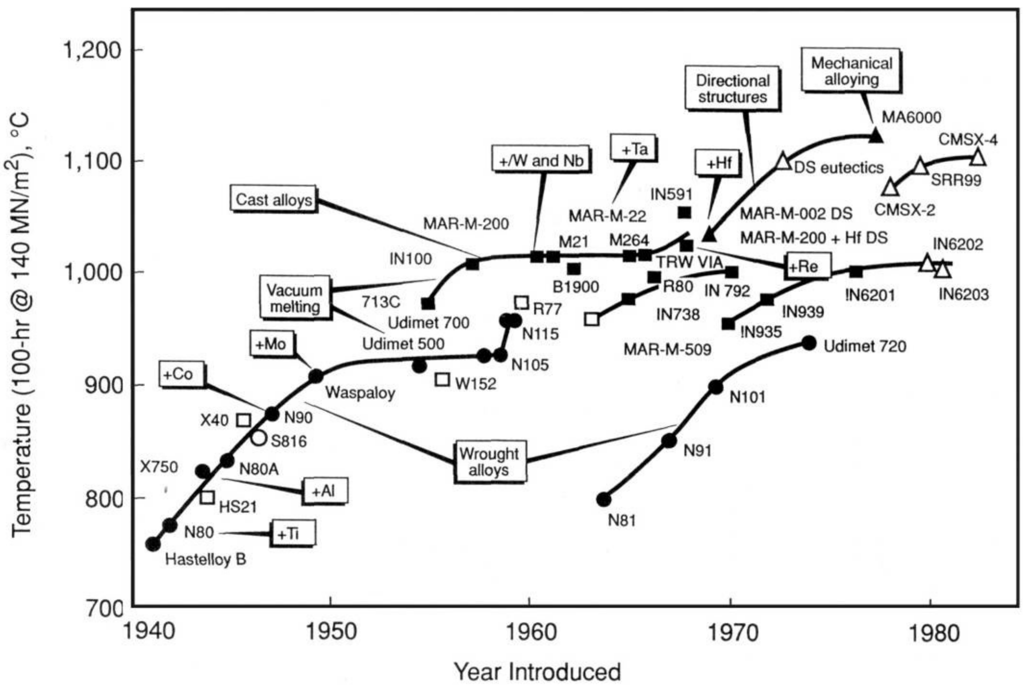

Fig. 3. The development of materials for turbine parts and the technologies of their manufacturing [5]

Table 1.
The chemical content of single crystal alloys [7]

Alloy	Cr	Co	Mo	W	Al	Ti	Ta	C	Hf	Other	ρ [Mg/m^3]
CMSX-4	6.5	9.0	0.6	6.0	5.6	1.0	6.5	-	0.1	3.0 Re	8.70
PWA 1484	5.0	10	2.0	6.0	5.6	-	9.0	-	0.1	3.0 Re	8.95
PWA 1480	10	5.0	-	4.0	5.0	1.5	12	-	-	-	8.70
Rene N4	9.0	8.0	2.0	6.0	3.7	4.2	4.0	-	-	0.5 Nb	8.56
CMSX-2	8.0	5.0	0.6	8.0	5.6	1.0	6.0	-	-	-	8.56
CMSX-3	8.0	5.0	0.6	8.0	5.6	1.0	6.0	-	0.1	-	8.56
TMS 63	6.9	-	7.5	-	5.8	-	8.4	-	-	-	8.48
SC 16	16	-	3.0	-	3.5	3.5	3.5	-	-	-	8.21
SRR 99	9.0	5.0	-	9.5	5.5	1.8	1.8	-	-	0.7 Nb	8.50

2.2. Directionally solidified and single crystal alloys

The directional solidification technique was introduced in the parts of gas turbines in the 1960s and 1970s. The directional solidification resulted in the obtainment of the boundaries with low modulus of elasticity. However, 2% Hf addition to DS Mar-M 200 alloy led to the increase in the plasticity of the grain boundaries [6].

The next stage of the directional solidification is the elimination of all the grain boundaries. One of the benefits of DS technique is the decrease of the amount or even a complete removal of such elements as: B, Zr and Hf. These elements reduce the temperature of melting of the alloys, which decreases their application temperature.

The directionally solidified and single crystal turbine blades have been the subjects of numerous articles summarizing many years of study in the USA as well as in Europe [2-6]. So far, probably the most renowned research project in the field of superalloys has been COST 501 programme.

Table 1 present the chemical content of the single crystal nickel base superalloys [7]. The chromium and aluminium content in the Ni base alloys determines their operating conditions. The low chromium content implies that the hot corrosion resistance of the alloys is insufficient for their application in stationary gas turbine part manufacture, whereas the majority of alloys including high rhenium, tungsten and titanium content has low foundry properties. SC 16 alloy, developed by ONERA, appears to be one of the very few acceptable alloys for the stationary gas turbines. The 16% chromium content leaves room for such application expectations, while the absence of rhenium, tungsten and titanium should improve its foundry properties. Nevertheless, even though it contains a comparatively high amount of chromium, it displays a surprisingly low corrosion resistance, whether coated or not. In fact, its oxidation resistance is lower to that of IN 738 LC alloy containing the same amount of chromium.

The 2nd generation of single crystal alloys. The research on single crystal alloys resulted in the development of the second generation of SX (Single Crystal) alloys, containing 3% Re. CMSX-4 and PWA1484 alloys, listed in Table 1, belong to this group. CMSX-4, the modified version of CMSX-2 alloy, is the major type of these. This alloy possesses a perfect solubility of γ' phase and is remarkably creep resistant in comparison with CMSX-2/3, whose creep resistance is higher about 35^{o}C. As well as this, during the hot corrosion burner rig trial at 899^{o}C, the alloy displayed extremely high resistance, comparable to IN792 alloy, containing 12.5% wt Cr. Fig. 4 demonstrates the microstructure of single crystal CMSX-4 alloy. Characteristic differences in the alloy structure can be distinguished depending on the cutting plane.

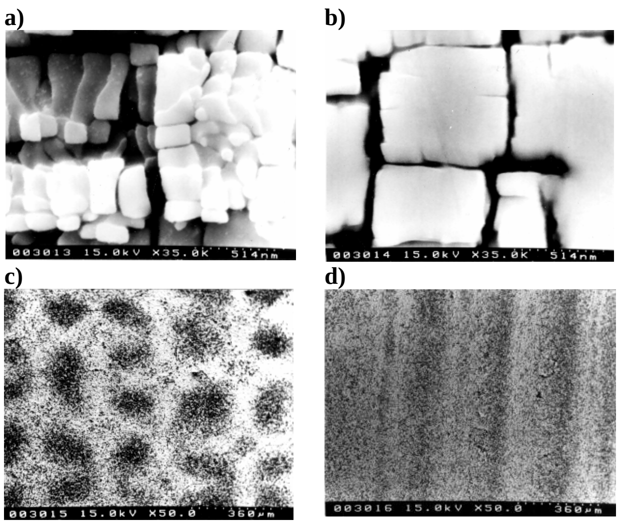

Fig. 4. The structure of single crystal CMSX-4 alloy: a) the cross-section of the bright area, b) the cross-section of the dark area, c) the cross-section, d) longitudinal section (L. Swadźba)

The 3rd generation of single crystal alloys. The third generation of single crystal cast materials should contain circa 6%wt Re. These alloys are likely to demonstrate increased creep resistance in comparison with the alloys including 3% wt Re. While the second generation of alloys contains γ' phase, which remains stable until 1149-1163^{o}C, the third generation of alloys should possess a significantly higher stability. Those materials are expected to present foundry properties similar to CMSX-4 alloy.

The current research realised within the leading programmes concentrate predominantly on the future applications of III generation alloys. There are, nonetheless, no universal alloys which would be able to meet the specific requirements with reference to mechanical properties, oxidation and hot corrosion resistance, and finally, manufacture costs.

3. Coatings

The technology and property analysis of the materials applied for gas turbine and aircraft engine parts indicates significant limitations concerning chemical content variability, their structure and manufacturing technology. The current construction solutions concerning enhancing the blade and the cooling system durability and turbine part operating temperature seem to have reached their limits. However, there is still much room for improvement since the maximal gas temperature has not been achieved yet (fig. 5).

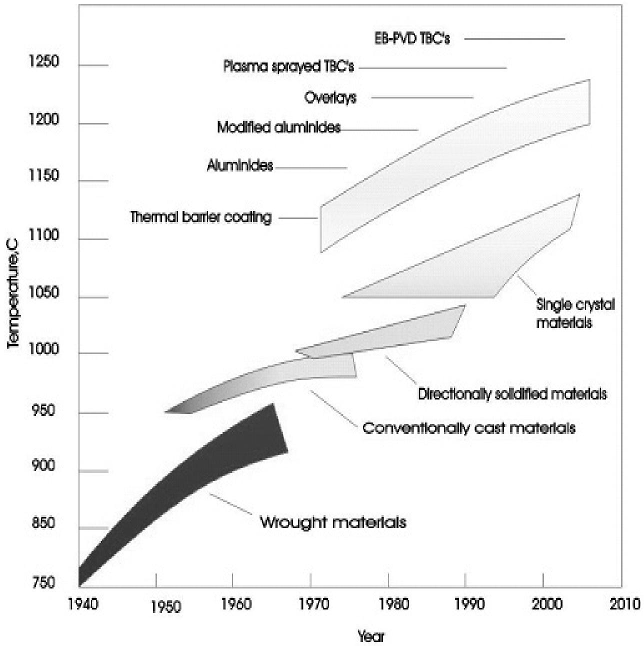

Fig. 5. The development of superalloys and heat resistant coatings [D. S. Rickerby, H. C. Low]

The increase in the durability and the operating temperature of turbine parts, particularly vanes, blades and combustion chambers, is possible with the use of protective coatings.

As presented in fig. 5, modern high temperature resistant coatings such as TBC, when applied with cooling systems and SX single crystal alloys are potentially remarkably beneficial.

The demand for coatings on the parts made of superalloys has led to their rapid development over more than three decades of their use. Their evolution has always been simultaneous to the development of construction materials. Nowadays, the engineers and constructors have plentiful coating deposition technologies at their disposal, enabling them to form adhesive, diffusion and adhesion-diffusion coatings, many of which are evolutionally modified common technologies, for instance chemical vapour deposition (CVD), physical vapour deposition (PVD) or thermal spraying technologies.

To obtain the coatings with CVD method, it is necessary to generate specific technological and thermo dynamical conditions in order to force coating deposition. Applying appropriate pressure, temperature, the amount and the flow of reacting gases enables the formation of heat resistant diffusion coatings on the outer surfaces of the blades, but it may also result in their deposition on the inner surfaces of cooling channels. The possibility of forming heat resistant aluminide coatings in these areas enhances the oxidation resistance of the blades; that is why it is considered to be functional and desired by turbine and aircraft users.

The evolution of ecologically pure vacuum technologies has also led to the significant development of PVD methods. The said coating deposition technologies are performed in vacuum chambers and typically employ high energy sources such as electron beam in EB-PVD method or arcing in Arc-PVD method. The coating formation occurs when the ionised atoms or particles are deposited at strictly defined temperature, which is measured on the surface of the coated parts. The PVD methods provide the means for depositing coatings which are extremely homogeneous in terms of thickness and possess a perfectly smooth surface, which does not require further treatment and improves the wear resistance of the coated parts. The Electron Beam Physical Vapour Deposition (EB-PVD) is the most technologically advanced PVD method, which is preferred currently for the deposition of thermal barrier coatings (TBCs).

The deposition of thermal barrier coatings on the parts of aircraft engines and gas turbines typically involves the application of thermal spraying method. Plasma spraying technique enables spraying a wide range of powdered materials. Moreover, although the technological process may be performed under atmospheric pressure, it might also be conducted in special low pressure chambers. For the reason of standards the spraying coatings need to meet, their manufacturing is performed with the use of manipulators, rotation and cooling systems and, in most cases, it is automatic, so the robot manipulates the plasma arc gun.

3.1. Diffusion aluminide coatings

Pack cementation method. Diffusion coatings are typically deposited during the diffusion aluminising process, or in some cases, during complex Al-Cr, Al-Si, Pt-Al, Ti-Al processes. During powder processes, the coated parts are placed in special containers, which are then covered with specific powder mixture, containing neutral filler such as Al_2O_3, the aluminium powder or alloy and the chemical activator. Subsequently, the sealed container is located in the furnace, where the chemical activator produces the transporting vapour source at a definite process temperature ranging from 700 to 1050°C. The diffusion aluminising process performed in this way usually lasts for up to twenty hours and requires strict powder mixture protection from oxidation. To obtain thickness or Al concentration diversified coatings, a number of types of the powder process are employed. The said types might be divided into high, moderate and low activation powders. During the aluminide coating deposition process at high temperature, about 1050°C, low aluminium content NiAl phases are created (low activity process), whereas at about 700°C, NiAl phases containing more aluminium are formed (high activity process).

„Out of pack” method. The out of pack method involves placing the coated parts in the container so that they do not have contact with powder mixture, which is generally granulated. The technological process is performed in retort furnaces or in vacuum furnaces. Throughout the course of coating deposition, additional neutral carrier gas is fed into the container, which enables the transfer of the coat forming gases, created during the process. Nowadays, several varieties of out of pack method are being applied, out of which sub-atmospheric pressure process, pulse vapour phase aluminising developed by SNECMA and the process performed on e.g. two mixtures of varied chemical content seem to be the most appealing. The main benefits of this process are as follows: the lack of coated material-powder contact, which notably improves the coating surface, more control over the course of the process, the increased tidiness of the process (in comparison with powder technologies) as well as the fact that aluminide coatings might be modified by elements increasing their heat resistance. Fig. 6 presents the microstructure of platinum modified aluminide coating, obtained in the platinising and aluminising processes [8].

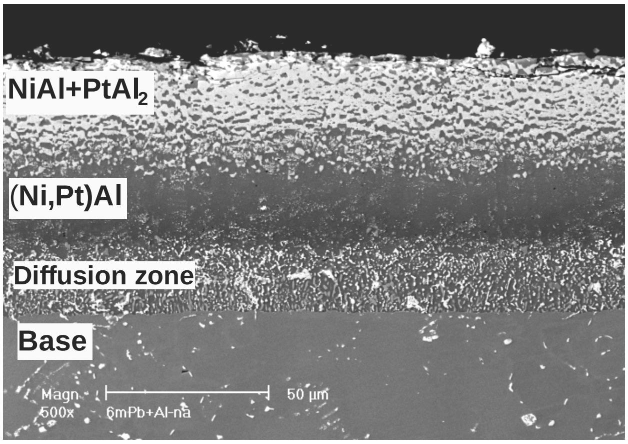

Fig. 6. The microstructure of platinum modified aluminide coating [8]

The increase in the heat resistance of the platinum modified aluminide coating has been confirmed in the laboratory cyclic oxidation test conducted at 1100°C in one hour cycles. Fig. 7 displays the test results presented in the form sample unit mass change as a function of the number of performed cycles [8].

CVD aluminizing process. The chemical vapour deposition process is the effect of evolution of the aforementioned methods applied for diffusion aluminide coating deposition. CVD process involves placing the turbine blades in the retort, which is fed with gas $AlCl_3+H_2$ atmosphere created in the outer reactor. Gas $AlCl_3$ is formed as a result of processing of HCl in the heated generator containing aluminium. Subsequently, $AlCl_3+H_2$ gases are preheated and fed into the retort when they reach about 1000°C. The CVD retort holding its charge is typically heated to the processing temperature in the bell type furnace, soaking pit or elevator furnace. The reaction gases leaving the retort are processed by the special gas neutralising system. This method of aluminising enables both outer and inner surfaces of the turbine blades to be coated simultaneously, particularly cooling channels, which might pose problems in other methods of coating. Apart from that, this technology provides the means for regulating the cooling rate, which is crucial on account of hot working parameters of several foundry superalloys.

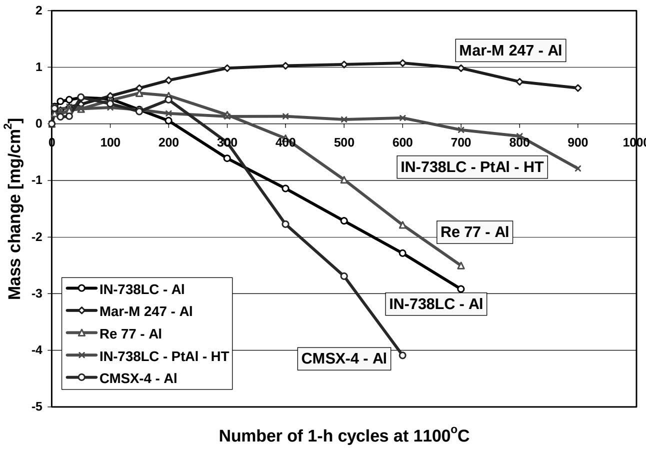

Fig. 7. The results of cyclic oxidation test performed on the selected superalloys with heat resistant coatings [8]

3.2. Thermal barrier coatings

The temperature of inlet gases may be increased thanks to the use of thermal barrier coatings on the combustion chamber parts, vanes and blades. The application of barrier coatings caused a decrease in the temperature of the employed superalloys by about 170°C in comparison with the temperature on the surface of the ceramic coating. What is more, the TBCs have decreased the amount of the necessary cooling air, while retaining constant temperature of exhaust gases, as well as increasing significantly the durability of the parts and their thermal deformation resistance [1]. The idea of thermal barrier coating application is presented in fig. 8.

The thermal barrier coatings are composed of the outer ceramic zone, usually consisting of ZrO_2 x Y_2O_3 and the bond coat, containing MCrAlY (M = Ni, Co, Fe). The insignificant value of thermal conductivity, characterising ceramic materials, triggers the temperature reduction in the interlayer above the bond coat, which is responsible for the rise in the oxidation and hot corrosion resistance.

The most common methods for obtaining thermal barrier coatings are APS (Air Plasma Spray), LPPS (Low Pressure Plasma Spray) or EB-PVD (Electron Beam Physical Vapour Deposition) [1]. The thermal spraying method is generally applied for producing TBCs on combustion chamber parts and vanes, whereas the blades are normally covered employing EB-PVD technology.

The microstructure of sample plasma sprayed thermal barrier coating, made of $ZrO_2x8Y_2O_3$ forming about 300 µm thick ceramic zone and the MCrAlY bond coat, which is about 100 µm thick, is shown in fig. 9. The yttria stabilised zirconia coating needs to possess a specific, strictly controlled porosity and micro cracks determining its cyclic temperature change resistance [9,10]. Fig. 10 demonstrates sample applications of plasma sprayed thermal barrier coatings on the aircraft engine combustion chamber and on the air cooled vane.

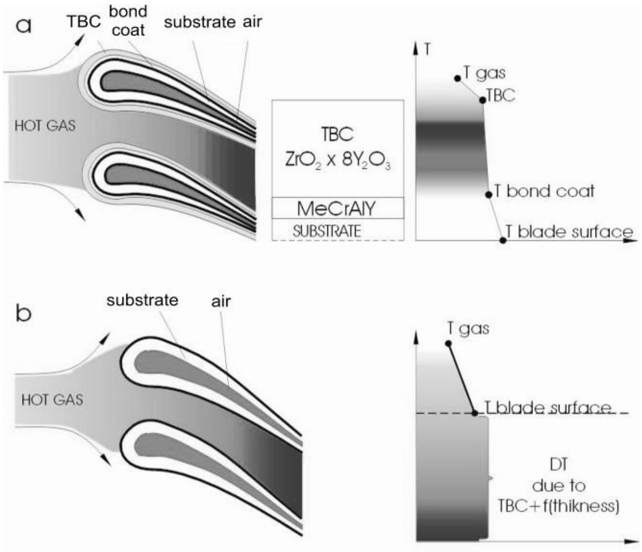

Fig. 8. The concept behind the application of TBC on the air cooled turbine blade: a) the temperature distribution on the TBC coated blade, b) the temperature distribution on the uncoated blade [S. J. Grisaffe, R. S. Levine].

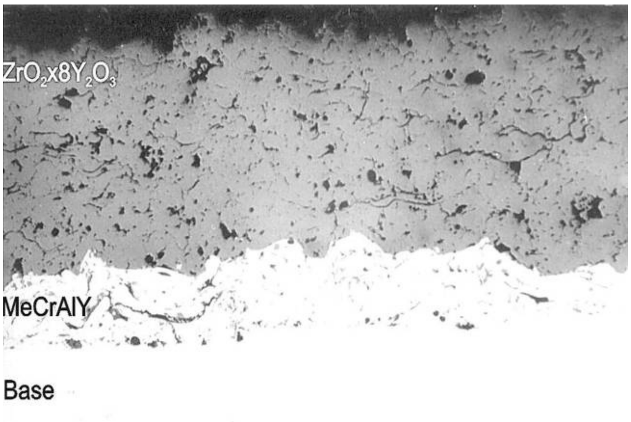

Fig. 9. The microstructure of plasma sprayed thermal barrier coating [L. Swadźba]

TBCs deposited by air plasma spraying and EB-PVD technology differ in terms of their structure and properties. Plasma sprayed coatings exhibit band structure, while EB-PVD deposited coatings are characterised by columnar structure [11]. The outlines of differences in the structure of both types of coatings are presented in fig.11 and 12. Plasma sprayed thermal barrier coatings are more vulnerable to thermal stresses, and their degradation occurs as a result of generation and development of numerous micro cracks, which might cause a complete spallation of the coating. It is a widely known fact that TGO (Thermally Grown Oxide) forming between the ceramic and the MCrAlY has a great impact on the durability of the thermal barrier coatings. The influence of the TGO layer, particularly its structure and thickness, on the properties of thermal barrier coatings is the subject of current study.

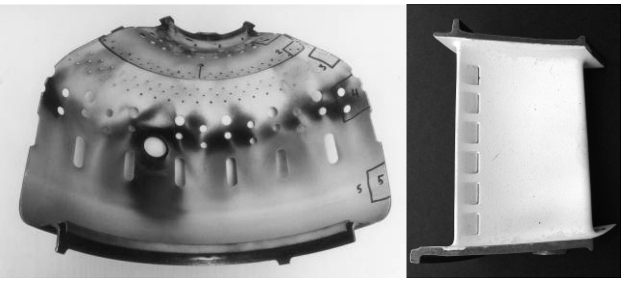

Fig. 10. Sample applications of plasma sprayed TBCs on the aircraft engine combustion chamber and on the air cooled gas turbine vane [L. Swadźba]

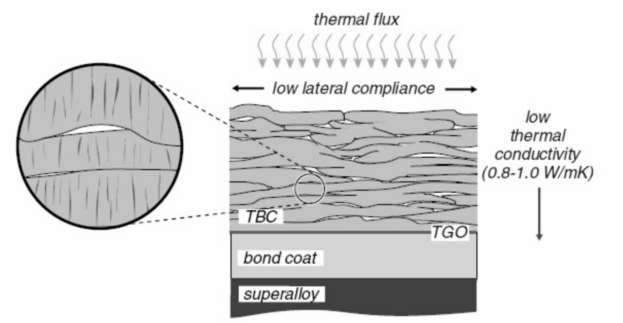

Fig. 11. The outline of thermal sprayed TBC microstructure [11]

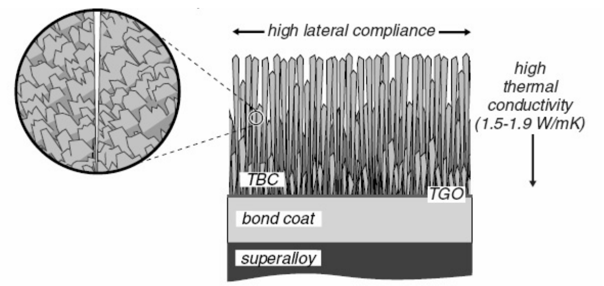

Fig. 12. The outline of EB-PVD TBC microstructure [11]

The application of EB-PVD technology enabled the obtainment of barrier coating structure which demonstrates much higher resistance to the thermal stress created in exploitation. Not only do the characteristic columns formed during the deposition display better stress compensation during thermal cycles, but also they prevent cracks on the coating-base border.

The development of thermal barrier coatings, especially those applied on gas turbine rotating blades, where much higher mechanical stresses appear, was the result of highly technologically advanced equipment use [12]. At present, there are only a few of companies manufacturing industrial equipment for TBC deposition, and the cost of their installation for gas turbine blades amounts for up to twenty million Euro. The general view of EB-PVD TBC installation is shown in fig. 13.

Fig. 13. The general view of EB-PVD TBC installation [12]

3.3. Erosion and corrosion resistant coatings

During aircraft engine operation, compressor blades are vulnerable to various types of failure, resulting from the specific, frequently aggressive factors. Mechanical damage resultant from the impact of particles of ingested foreign matter, e.g. from the airstrips, is one of the most common problems.

All scratches and indentations etc. constitute accidental damage and, as such, are extremely difficult to prevent. As well as that, the compressor blades are also subject to the erosive-corrosive impact of inflow dusty air. Their damage generally takes the form of pinholes appearing chiefly on the leading edge and on the pressure said of the blade [13].

The erosion dents, particularly these placed on the leading edge of the compressor blades, initiate corrosion by retaining humidity (fig. 14).

The injured coherence of the material in the corrosive environment forms the structural foundation initiating fatigue fracture, which poses a threat to one of the crucial elements of the compressor blades.

The erosive damage of the aircraft engine parts may be prevented by applying protective coatings. The earliest of these, varnish coatings, demonstrated extremely low efficiency in terms of erosion and corrosion protection, being particularly susceptible to destruction consequential to their exposure to the stream of dusty air. The fastest degradation occurred on the leading edges of the blades. The prolonged flow of the stream of dusty air could accelerate notably the erosion process in the blade material, while the corrosion processes are determined by the electrochemical and chemical interaction of the material and the surrounding environment, e.g. coastal environment. The enumerated destructive phenomena occur mainly during operation, sometimes varying in intensity.

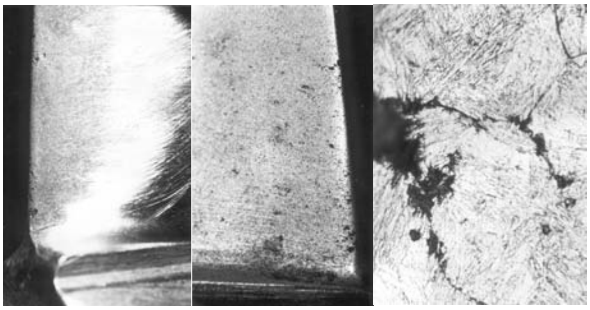

Fig. 14. Erosive-corrosive damage of the compressor blade made of martensitic steel following the operation [13].

The development of PVD technology aims at the enhancement of coating properties and at extending their application area. The aircraft engine compressor blades constitute one of the most appealing, currently developed and researched PVD obtained coatings application [13-15]. The protective coatings intended for such specific construction elements must meet numerous requirements, both in terms of their mechanical properties and in corrosion and wear resistance.

Arc-PVD method is a type of PVD method enabling the formation of a wide range of protective coatings, also the multilayer ones [16]. It is characterised by high ionisation degree and a comparatively high deposition capacity. The chief advantage of the said method is its capability of creating the coatings which are not only very hard and wear resistant, but also extremely corrosion resistant (fig. 15).

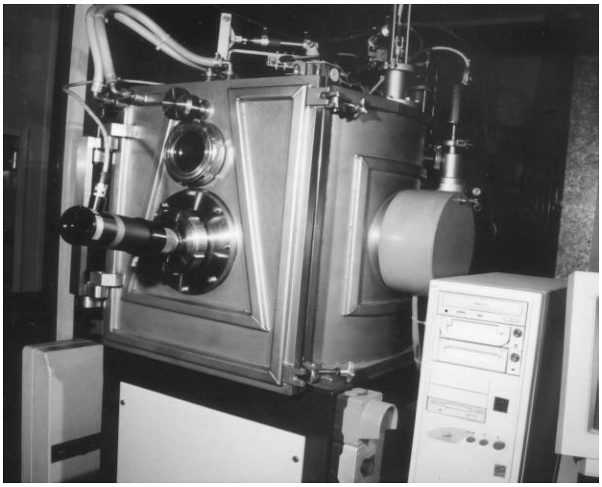

Fig. 15. The general view of the PVD equipment applied during the study on erosion and corrosion resistant coating deposition [B. Mendala]

The research on the extension of PVD deposited coating application has been continuing for several years now. For a couple of years, the focus of the technology engineers, besides the titanium nitride coatings, has been on the chromium nitride coatings [17,18]. The technologies of the deposition of complex-structured coatings, for instance CrN based multilayered coatings or coatings modified with elements such as chromium or aluminium, are developed and presented on fig. 16 [18,19].

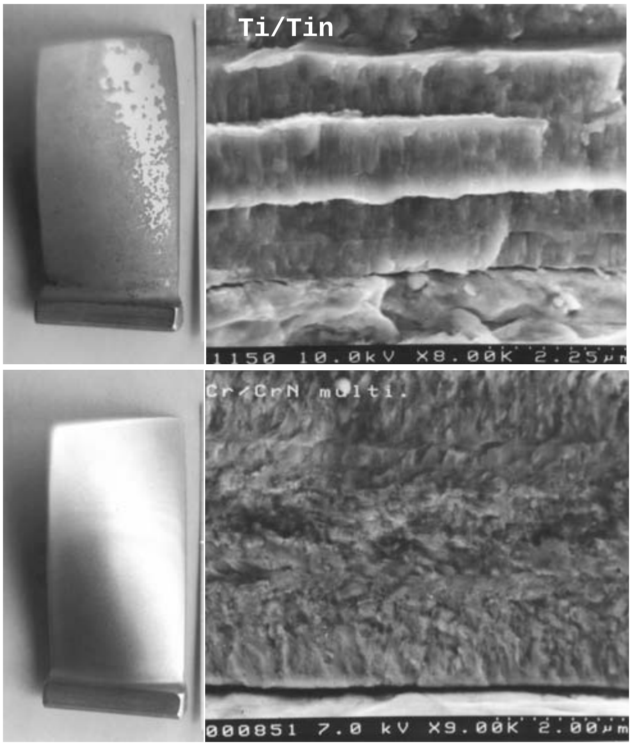

Fig. 16. Fracture morphology of Ti/TiN and Cr/CrN multilayer coatings deposited by Arc-PVD method on compressor blades made of martensitic stainless steel. View of coated compressor blades after engine test

Out of the coatings obtained with PVD methods, chromium nitride demonstrates a relatively higher corrosion resistance when compard to other nitride coatings, owing to its fine-grained, compact structure and high density [20-22]. The high density of chromium nitride coatings, which determines their corrosion resistance for the most part, might be increased by applying interlayers of chromium or aluminium [20].

The Arc-PVD deposited chromium coatings demonstrate the highest adhesion to the steel base, reaching as high as 80 N, and, additionally, provide a perfect link for the subsequent layers of much harder chromium nitride in the multilayered Cr/CrN type coatings. As well as that, attempts have been made to deposit aluminium adhesive coatings and multilayered Al/AlN coatings.

The Al based coatings are the potential cathodic-protection coatings. Obtained with magnetron sputtering, the coatings display excellent corrosion resistance. However, they possess rather low tribological properties.

Obtaining the coatings displaying increased corrosion resistance by means of PVD methods is certainly justified and advisable, especially in automotive and aircraft industries. Al, AlMg, Cr, Cr/CrN and Cr/CrN/Al coatings deposited on steels are expected to replace the cadmium coatings obtained chiefly in galvanic processes. Fig. 17 displays a set of aircraft engine compressor blades made of type EI 962 martensitic stainless steel with Cr/CrN multilayer coating obtained by Arc-PVD method.

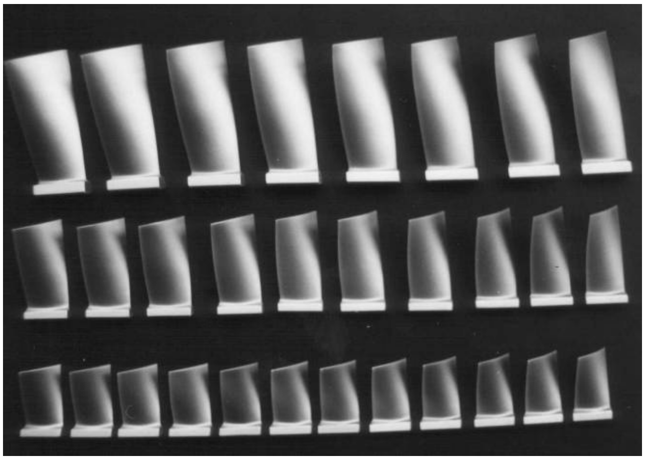

Fig. 17. Set of compressor blades coated with Cr/CrN multilayer coating deposited by Arc-PVD method [L. Swadźba, B. Mendala]

The multiplayer Arc-PVD coatings consisting of chromium nitride and including chromium as interlayers demonstrate high erosion resistance. This type of coatings is also know as the so-called smart coatings, since their structure determines the wear intensity according to the operating conditions. While in function, the aircraft engine works in cycles, heating and cooling cyclically. Additionally, it is used in diversified environment, and subjected to the most powerful loads while taking off, when it works with its maximal power. Such conditions puts compressor blades at risk of damage resultant from corrosion as well as erosion caused by the pollution in the air flowing through the engine. The sand and dust ingested with the air hit the surface of the compressor blades, especially their leading-edge, at various angles and energy levels. Large particles mainly hit the blade at an 90° angle and are crushed on the leading-edge into dust, which abrades the blade material even more intensely in the trailing-edge at small 20-30° angles. The coatings composed of alternating hard nitride zones and soft chromium zones adjust to the present operating conditions. The relatively soft chromium zones in the area of the leading-edge have been confirmed to suffer less damage, while the hard nitride zones of the trailing-edge provide effective erosion protection. The properties of the multiplayer Cr/CrN coatings have been proven by the conducted engine trials, which have also demonstrated much worse protective properties of the Ti/TiN coatings.

4. Conclusions

The efficiency and reliability enhancement of the engines will probably be achieved as a result of application of protective coatings and through a notable reduction of their manufacturing costs. The new trend in the coating system development will most likely include depositing multilayer, gradient and modified coatings, whose properties will surpass the ones obtained at present. Applying single crystals as turbine blades, designing highly effective blade cooling systems, employing CVD technology to produce heat resistant diffusion coatings, spraying thermal barrier coatings prepared for functioning in temperatures higher than achieved so far, as well as using EB-PVD method for rotating blades are the subjects of the current research of the authors of the present work. In Poland, new modern laboratories with necessary appliances and technological equipment for the research on new single crystal alloys for aircraft engine parts are presently being opened as parts of research programmes. Protective coating laboratories equipped with modern PVD and CVD apparatus are founded. The programmes follow the newest trends in the development of Polish aircraft industry.

The present article constitutes a summary of many years of collaborative research programmes of The Silesian University of Technology, WSK-PZL Rzeszów and Pratt&Withney. The projects have been co-funded by the Scientific Research Committee.

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