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Modern materials used for environmental barrier coatings – a review

Nowoczesne materiały stosowane na powłoki EBC – przegląd

In this article, the materials used for EBC coatings, representing next stage in the development of heat-resistant layers, and thermal barrier coatings are reviewed. In the introduction, the design of gas turbine is characterized, as well as the materials used for the hot part components and the requirements for protective coatings. Ceramic materials that can be an alternative to currently used nickel superalloys for turbine blades are also described. The requirements for EBC coatings were analyzed and then the various types of EBC coatings were characterized, as well as their degradation mechanisms.

Keywords: environmental barrier coatings, high temperature corrosion, oxidation, turbine blades

*W artykule dokonano krótkiego przeglądu materiałów stosowanych na powłoki EBC (*environmental barrier coatings*) reprezentujących kolejny etap zaawansowania warstw żaroodpornych i powłokowych barier cieplnych (TBC –* thermal barrier coatings*). Opisano konstrukcję turbiny gazowej i materiały stosowane do produkcji elementów części gorącej oraz wymagania w zakresie powłok ochronnych. Opisane zostały również materiały ceramiczne, które mogą być alternatywą dla obecnie stosowanych nadstopów niklu używanych do wytwarzania łopatek turbin. Przeprowadzono analizę wymagań dotyczących powłok EBC, a następnie scharakteryzowano poszczególne rodzaje tych powłok, a także mechanizmy ich degradacji.*

Słowa kluczowe: środowiskowe bariery cieplne, EBC, korozja wysokotemperaturowa, utlenianie, łopatki turbin

1. Materials and coatings currently used for turbine blades

A gas turbine is an internal combustion engine whose function is to convert gas energy into mechanical energy, which in turn drives a generator that produces electricity. The main parts of a gas turbine are the intake, compressor, combustion chamber, turbine and exhaust nozzle [1, 2]. Air from the environment is drawn into the compressor, where it passes through alternating rows of steering and rotating blades. The pressure and temperature of the air increases, resulting in a decrease in its volume. Compressed air passes into the combustion chamber, where fuel-air mixture is ignited. The resulting hot exhaust gases are expanded and passed through the turbine, which drives the compressor and auxiliary units (alternator, pumps). Exhaust gases are discharged through an exhaust channel. In order to increase the efficiency of gas turbine, it is necessary to increase temperature in the combustion chamber. This would allow the increment of air pressure. As a result, thrust of an engine would be greater, which is beneficial to the efficiency of whole turbine [3].

The components operating under the most demanding conditions, i.e., extremely high temperature, corrosive environment and huge loads, are high-pressure turbine blades. The blades are subjected to shear and bending stresses and thermo-mechanical loading cycles under oxidizing conditions at high temperatures [3]. Therefore, they should have high fatigue strength, resistance to high-temperature oxidation and creep resistance [4].

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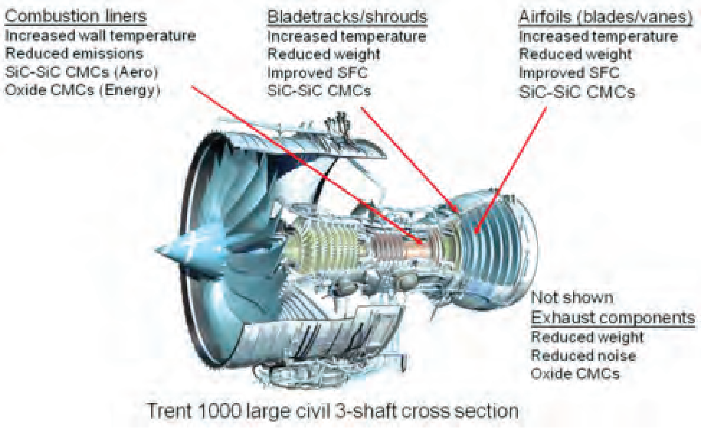

Fig. 1. Potential use of CMC composites in an aircraft engine turbine

Source: [22].

Rys. 1. Potencjalne zastosowanie kompozytów CMC w turbinie silnika lotniczego

Źródło: [22].

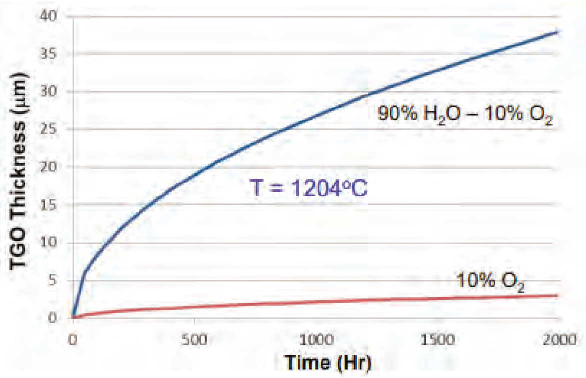

Fig. 2. Oxidation rate of SiC/SiC composite in an environment containing steam (90% H_2O) and in dry oxygen (10% O_2)

Source: own elaboration based on [39].

Rys. 2. Szybkość utleniania kompozytu SiC/SiC w środowisku zawierającym parę wodną (90% H_2O) oraz w suchym tlenie (10% O_2)

Źródło: opracowanie własne na podstawie [39].

For several decades, nickel superalloys have been used for the production of high-pressure turbine blades due to their high strength at operating temperature [5]. The blades are cast as single-crystal in the Bridgman process [6, 7]. After casting, special cooling holes are made to circulate cooling air drawn from the compressor, lowering the temperature of gases coming into contact with blade surface [8]. This surface is protected by TBC (thermal barrier coatings), consisting of two layers [9]. The ceramic layer (TC – top coat) is the outer layer of TBC system, whose function is to protect against hot gases and erosion, as well as to serve as a thermal insulation [10]. It is manufactured using atmospheric plasma spraying (APS) [11] or EB-PVD (electron beam physical vapour deposition) methods [12].

The interlayer (BC – bond coat) is the inner layer of the TBC system, which is designed to provide required oxidation resistance. Typically MCrAlY [13] and aluminide bond coats are used [14, 15]. During pre-oxidation, a protective oxide (TGO – thermally grown oxide) layer is formed on its surface [16]. TGO is tight and adherent to the substrate, thus minimizing its oxidation kinetics and ensuring good adhesion of the outer ceramic layer [17]. The substrate, often made of single-crystal nickel superalloy, is responsible for transferring mechanical loads [2]. Improvements in thermal barrier coatings and cooling mechanisms made it possible to increase the inlet temperature of exhaust gases on a high-pressure turbine to 1500°C, increasing efficiency and reducing emissions of pollutants into the atmosphere, including carbon dioxide. However, the achieved operating temperature of single-crystal nickel superalloy blades is approaching the substrate's melting point, which hastens works on new materials and coatings with better heat resistance, capable of operating at even higher temperatures [18].

2. Ceramic matrix composites as material for turbine blades

In recent decades, the development of nickel superalloys and heat-resistant TBC coatings has led to a significant increase in gas turbine operating temperature. However, the continuing trend to improve performance and reduce aircraft emissions has led to a search for materials that can provide even higher turbine operating temperatures [5, 19]. The solution seems to be ceramic matrix composites (CMC), which offer properties that significantly exceed those of conventional superalloys [20, 21]. Many types of CMC are available, characterized by a wide range of properties [22]. These include C/C [22], C/SiC [17], SiC/SiC [23] and Ox/Ox [24] composites. Due to their exceptional high-temperature mechanical properties, low weight, thermal shock resistance and very good high-temperature oxidation resistance, SiC/SiC composites are of particular interest to researchers (Fig. 1) [18, 25, 26].

SiC/SiC composites consist of polycrystalline continuous SiC fibers of about 10–15 µm in diameter, with a BN coating, and a matrix also made of SiC. The components of SiC/SiC composites should have high thermal stability in the operating temperatures, creep resistance and exceptional resistance in corrosive environments [27]. This allows for long-term operation of the component at the specified temperature, time and stress state [28]. The fibers should be continuous, with a diameter as small as possible, strength of about 3000 MPa, a Young's modulus of about 400 GPa, and the ability to maintain these properties at the highest possible temperature under high load for a long time [29]. In addition, the material should have low porosity and high thermal conductivity, while the grain diameter should be about 500 nm [18].

The main disadvantage of SiC/SiC composites, limiting their applicability for turbine blades, is their insufficient corrosion resistance in water vapor condition [30–32]. During operation, SiO_2 oxide is formed on their surface, which reacts with the product of aviation fuel combustion: water vapor, forming volatile $Si(OH)_4$ [33]. In addition, the presence of impurities (sand, volcanic dust, etc.), responsible for CMAS (calcium-magnesium-alumino-silicate) corrosion, causes accelerated destruction of SiC/SiC elements, leading to a rapid degradation of entire composite [34]. The estimated rate of this process is 1 µm/h for the usual conditions in an aircraft engine gas turbine (exhaust gas temperature 1350°C, gas velocity 350 m/s, partial pressure of water vapor 100 mbar) [35].

Without adequate protection, the durability of structural components made from these composites is unacceptable (Fig. 2), precluding their use in hot aircraft engine parts. For the above reasons, coatings that can provide adequate SiC/SiC protection against water vapor and CMAS corrosion, known as environmental barrier coatings (EBCs), have been sought since the 1980s [32, 36–40].

3. Environmental barrier coatings (EBCs)

CMC composites are very susceptible to CMAS corrosion [41] and loss of material due to evaporation of formed oxides in a water vapor conditions [42, 43], therefore EBC coatings are used to

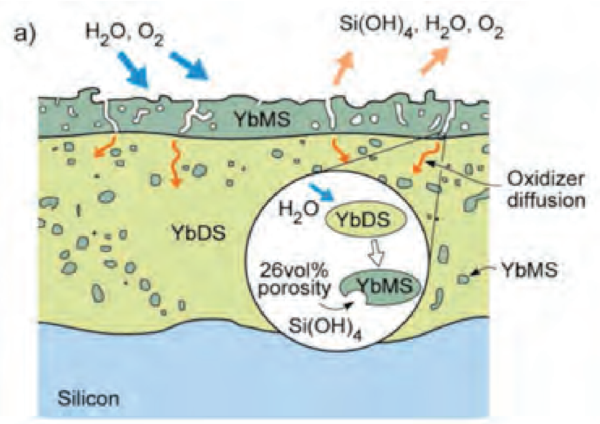

Fig. 3. Schematic representation of the volatilization of SiO_2 from the initial YbDS coating and formation of YbMS: a) initial stage, b) later stages
Source: [45, p. 1758].
Rys. 3. Schemat przedstawiający wyparowywanie SiO_2 z początkowej powłoki YbDS oraz powstawanie YbMS: a) początkowy etap, b) końcowy etap procesu
Źródło: [45, s. 1758].

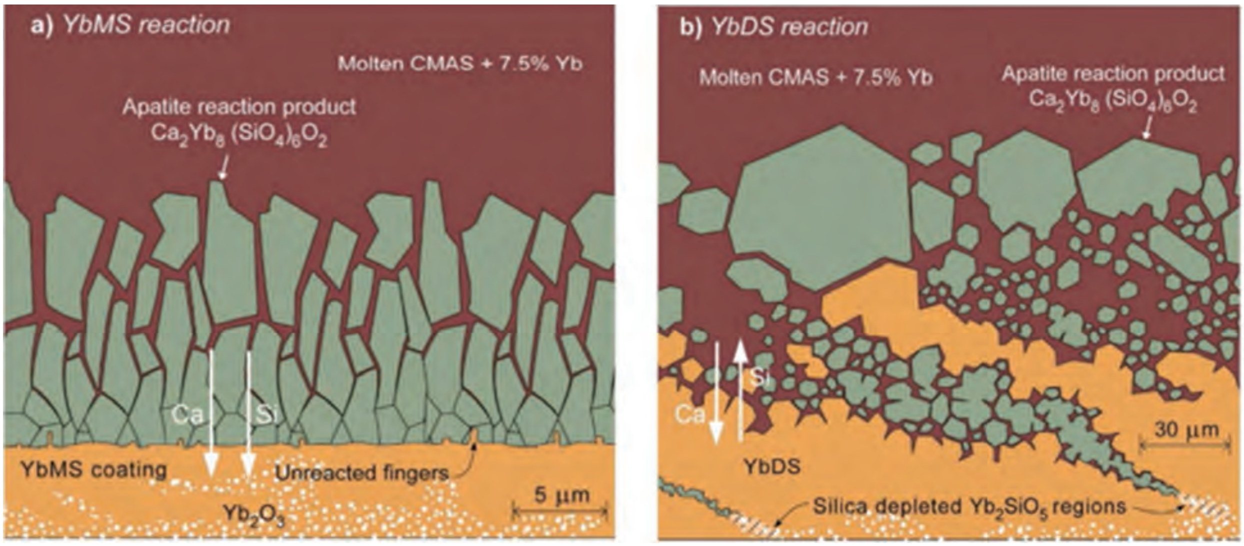

Fig. 4. CMAS reaction mechanism with EBC outer coating (a) and CMAS penetration mechanism along EBC grain boundaries with subsequent fracture cracking (b)
Source: [45, p. 1761].
Rys. 4. Mechanizm reakcji CMAS z zewnętrzną powłoką EBC (a) oraz mechanizm penetracji CMAS wzdłuż granic ziarn EBC z następnym pękaniem szczelinowym (b)
Źródło: [45, s. 1761].

protect them [44]. Literature analysis indicates that the material used as EBC should meet following requirements:

- During operation, there are cyclic temperature changes that cause expansion and contraction of the material, as well as thermal stresses. To avoid these, EBC components should have similar thermal expansion coefficient [45, 46].
- The chemical compound used should not exhibit polymorphic transformation at elevated temperatures, as it leads to a change in the material volume, being the cause of cracks and porosity in coating [45, 47, 48].
- Silicon should be avoided when designing the chemical composition, because it reacts with water vapor during operation, resulting in the formation of volatile products $Si(OH)_4$ that cause material recession [45, 49, 50].
- Attention should be paid to the stability and chemical compatibility of EBC components at elevated temperatures and long operating times, as reactions can occur between them, leading to undesirable products [45, 51, 52].
- The coating material should be resistant to CMAS corrosion (a mixture of molten compounds: CaO-MgO-Al_2O_3-SiO_2) [45, 53, 54].

The EBC coating must exhibit good adhesion to the substrate, so a silicon interlayer is used, which provides a strong chemical bond and has a similar linear thermal expansion coefficient of to the SiC/SiC composite substrate [40–56].

4. Degradation mechanism of EBC coatings

Environmental barrier coatings are designed to protect components made of SiC/SiC composites that operate in aggressive corrosive environments containing water vapor at extremely high temperatures. When evaluating the durability of these coatings, it is necessary to take into account a number of factors that cause their degradation.

The first is oxidation, which, as in the case of TBC coatings, causes the formation of a thin TGO layer (in this case composed mainly of

SiO_2 oxide) [57]. Once the critical thickness is reached, inner stresses cause cracking and separation at the scale/coating interface [55, 58]. In the case of an ytterbium disilicate (YbDS) coating, oxidation results in the evaporation of outer coating material and formation of porosity (Fig. 3), which facilitates the diffusion of oxidant ions that attack sensitive silicon interlayer (the reaction produces volatile silicon hydroxide). In addition, during this process, polymorphic transformation of disilicates into monosilicates (YbMS) of ytterbium occurs. It results in a 26% reduction in volume, which causes the appearance of significant tensile stresses due to the different CTE (thermal expansion coefficient) value of ytterbium monosilicate. This results in the formation of transverse cracks that are pathways or easy diffusion for oxidant ions and contribute to faster TGO growth [25, 45, 59].

Another problem is recession (loss of material due to evaporation), which for the BSAS (barium-strontium-alumino-silicate) coating, after 1000 h of operation, reduces sample thickness by 70 µm (1400°C, v = 24 m/s). This is an unacceptable degradation rate for structural components in the hot part of an aircraft engine [55].

An extremely important factor causing the destruction of EBC coatings is CMAS corrosion, which is particularly dangerous in the liquid phase (T_m = 1200°C, so well below the expected operating temperature of EBC coatings of 1500°C and above). So far, two main mechanisms responsible for the destruction of EBC coatings due to CMAS corrosion have been identified (Fig. 4). First involves the reaction of molten CMAS with the outer EBC coating made of rare earth monosilicates. EBC is being dissolved with subsequent recrystallization of yttrium monosilicate and apatite Y-Ca-Si, which form characteristic needles (Fig. 4a). The second possible mechanism involves the penetration of liquid CMAS along the grain boundaries of the disilicates deep into EBC layers, with subsequent "crevice" cracking through the slow motion of molten CMAS (Fig. 4b). If CMAS reacts with a EBC coating made of rare earth disilicates, rare earth apatites are formed, coating material is lost, cracks and pores develop. However, the chemical composition of CMAS varies and it may contain less calcium compounds. Then degradation occurs through fracture cracking, which in a short period of time leads to the loss of coating cohesion and its separation. Studies conducted [60] show that both mono and ytterbium disilicates are very sensitive to CMAS corrosion. After 200 h at 1500°C, CMAS penetrated the entire thickness of the 4 mm sample.

Any foreign objects (birds, debris, chipped coating fragments, etc.) entering through the turbine inlet can cause damage by impacting internal structural components. This phenomenon is particularly dangerous for SiC/SiC composites with EBC coatings, as any damage to the coating results in an immediate loss of integrity and accelerated degradation of the substrate material [45]. In the course of research [61], it was found that for a 2D mat of SiC/SiC composite coated with plasma-sprayed EBC coating, the coating provides protection from impact of chromium steel particle with HRC hardness > 60 for velocities not exceeding 160 m/s.

One of the EBCs disadvantages is decomposition of disilicate to monosilicate in water vapor condition, according to reactions [62–65]:

$$Yb_2SiO_5(s) + 3H_2O(g) \rightarrow Yb_2Si_2O_7(s) + 2Yb(OH)_3(g), \quad (1)$$

$$Yb_2Si_2O_7(s) + 2H_2O(g) \rightarrow Yb_2SiO_5(s) + Si(OH)_4(g). \quad (2)$$

This degradation process also takes place in very high temperature of about 1350°C [65]. SiC/SiC composites offer the possibility of increasing the operating temperature of an aircraft engine well above 1500°C, which could translate into increased efficiency and lower emissions of harmful gases into the atmosphere. However, they must be adequately protected from aggressive corrosive agents that cause their rapid degradation. Therefore, the search is underway for modern EBC coatings that meet the requirements outlined above [66, 67].

5. Materials for environmental barrier coatings

5.1. Mullite

Initial works on coatings for ceramics (SiC and Si_3N_4) in the late 1970s and early 1980s were aimed at extending the life of cylindrical components in corrosive environments [67, 68]. The similar coefficient of thermal expansion and chemical compatibility with SiC and Si_3N_4 ceramics made mullite a great candidate as a coating material for SiC and Si_3N_4 [32, 69–71]. Mullite ($3Al_2O_3 \cdot 2SiO_2$) is a ceramic material with a high melting point, low thermal conductivity (~$5 \cdot 10^{-6}$ 1/°C), high electrical resistivity and good creep resistance [67, 72].

Initially, mullite coatings were produced by conventional atmospheric plasma spraying (APS). Lee, Miller, and Jacobson [73] obtained mullite coating by conventional APS process. After 48 h oxidation (2-hours cycles) at 1000°C in air, delamination and a high proportion of cracks were observed in the coating microstructure. This was attributed to the metastable amorphous phase that forms during rapid solidification of the mullite on a cold substrate. Subsequent exposure of the mullite coating at ~1000°C causes crystallization of the amorphous phase, and the accompanying shrinkage leads to cracking and delamination of the coating [67, 74]. The modification of conventional APS process improves properties of the obtained mullite coatings – there is a significant increase in adhesion and fracture resistance [73]. Coating obtained via modified process was subjected to 48 h oxidation (2-hours cycles) at 1000°C in air. It was characterized by a small number of cracks and good adhesion to the substrate.

Further research [75, 76] allowed the development of mullite coatings that showed no damage after 1200 h of cyclic oxidation at 1300°C, in an air atmosphere. The paper [77] examined the behavior of coatings consisting of mullite and a mixture of silicon and mullite during oxidation under the following conditions: 200 h at 1300°C and 300 h at 1380°C. TGO layer composed of SiO_2 oxide with a thickness of ~25 µm formed at the mullite/SiC interface. Discovery of SiC recession under steam limited the use of mullite as a coating material for SiC and Si_3N_4. Low stability of mullite in contact with water vapor caused selective evaporation of SiO_2 and exposure of porous Al_2O_3 layer [73]. Tests have also been carried out [32, 78], in which the use of a coating consisting of mullite and ZrO_2 was studied. In the work [78], during isothermal annealing in a water vapour atmosphere, the formation of SiO_2 scale at the SiC/mullite interface was observed. The failure of the mullite/ZrO_2 system lay in the CTE mismatch. Despite similar CTE values for SiC and mullite, the thermal expansion of ZrO_2 is almost twice that of SiC. This causes cracks in the coating during cyclic oxidation and eventual delamination [32, 71].

5.2. First generation of EBCs

BSAS ($1 - x$BaO $\cdot$ xSrO $\cdot$ $Al_2O_3 \cdot 2SiO_2$, $0 \le x \le 1$), has become another candidate for EBC material, due to its similar CTE value (about $4.5 \cdot 10^{-6}$ °C^{-1}), low Young's modulus (~100 GPa for high-density BSAS) and high stability in contact with water vapor [73]. The disadvantage of BSAS is the formation of a low-melting (~1300°C) eutectic during reaction with SiO_2 as a result of oxidation, which causes EBC degradation and premature failure at temperatures above ~1300°C [74]. The use of a mullite interlayer eliminated the problem associated with BSAS chemical incompatibility. Since mullite is not a highly durable material under steam oxidation conditions, interlayers consisting of mullite and 20 wt. % BSAS were developed. Subsequent studies [70, 78–80] identified silicon as the most effective interlayer material due to its high oxidation resistance and thus increased durability under cyclic oxidation conditions [67, 70]. By the late 1990s, the latest EBC coatings had a three-layer structure: a silicon interlayer, a mullite + BSAS type layer, and a BSAS top layer [67, 70].

The CMC composite, coated with Si/mullite + 20% BSAS/BSAS was cyclically oxidized at 1310°C for 100 h and 1316°C [74] for 1000 h (1-hours cycles) in a steam atmosphere. For 1310°C neither degradation nor oxidation of EBC was observed; for 1316°C no formation of SiO_2 and no glassy zone between the layers was observed. The pores and "pockets" of glassy phase in the BSAS layer formed at 1316°C can lead to peeling and falling off of the coating, reducing its durability. The addition of interlayer did not completely eliminate the problem associated with the formation of a glassy phase during the reaction between BSAS and Si. Moreover, the problem increased with increasing temperature and with further penetration of glassy phase deep into the surface layer. That is why for this type of coatings ~1300°C is their upper temperature limit [74, 77].

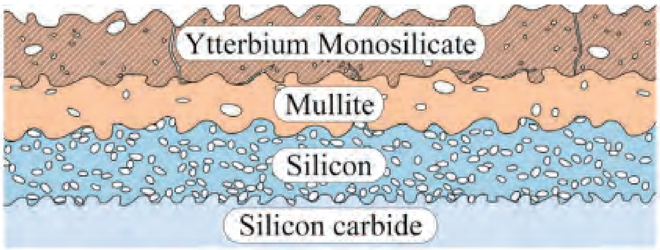

Fig. 5. Schematic illustration of tri-layer EBC structure, produced using atmospheric pressure plasma spraying (APS) method

Source: [82, p. 3083].

Rys. 5. Schemat powłoki EBC wykonanej z wykorzystaniem technologii natryskiwania plazmowego przy ciśnieniu atmosferycznym (APS)

Źródło: [82, s. 3083].

5.3. Second generation of EBCs

In order to achieve 1482°C as the target operating temperature for EBC coatings, the US space agency NASA in 1999 began a search for another candidate EBC material. Rare earth silicates were chosen as they possess high stability in water vapor (associated with low SiO_2 activity), high melting point and often similar CTE to CMC. Monosilicates (RE_2SiO_5, RE – rare-earth elements) compared to disilicates ($RE_2Si_2O_7$) have better stability in water vapor and higher melting point (~1950°C for Yb_2SiO_5 and ~1850°C for $Yb_2Si_2O_7$), while disilicates have closer CTE values to the substrate composite material [81]. The average CTE values and melting temperatures of rare earth compounds, SiC, Si and Si_4N_5 are shown in Table 1.

During oxidation in a water vapor atmosphere of an EBC system consisting of $Si/Yb_2Si_2O_7$ it was observed [83], that steam penetrates through $Yb_2Si_2O_7$ into Si, where it reacts with it to form SiO_2 at the $Si/Yb_2Si_2O_7$ interface. The thickness of formed SiO_2 is mainly controlled by the oxygen partial pressure and thickness of the ytterbium disilicate, and is proportional to the corrosion time [84]. A $Si/Yb_2Si_2O_7$ bilayer coating applied to a substrate of sintered α-SiC was subjected to cyclic oxidation in steam, where one cycle consisted of 60 min at 1316°C and 10 min at 110°C [85]. The thickness of SiO_2 scale increased with the number of cycles to 2.5 μm for 2000 cycles. Vertical cracks were observed for samples oxidized for more than 1000 cycles, where the thickness of the formed scale exceeded 1 μm. The SiO_2 formed was identified as *α*-crystobalite. It is believed to undergo polymorphic transformation into *β*-crystobalite at 1316°C, which can lead to high residual stresses during repeated oxidation cycles [85, 86].

The second-generation EBC coatings consist of three layers: a silicon interlayer, a mullite-based interlayer and an outer layer made of rare earth silicates. The function of Si interlayer is to impede the oxygen or water vapor transport, that penetrate the outer layers of the coating to form SiO_2 oxide with the composite substrate. During the reaction, oxidizing molecules are consumed, which, reaching the bonding layer, form a diffusion barrier and retard the transport of oxidizing molecules into the substrate. It is necessary to use interlayer for monosilicates, because otherwise formation of SiO_2 scale would happen, followed by premature flaking and falling off at the coating/composite substrate interface due to different CTE values and low hardness of the scale [81, 87]. The mullite interlayer acts as a diffusion barrier to the oxidizing element simultaneously preventing unwanted reactions in the solid state. The outer layer made of ytterbium monosilicate provides high chemical stability and protection against recession phenomena in contact with water vapor [87, 88]. Fig. 5 shows a scheme of a second-generation EBC coating.

In the paper [89], a SiC/SiC composite, coated with an EBC coating with the following three-layer structure: Si/mullite + 20% BSAS/Yb_2SiO_5, was subjected to cyclic oxidation at 1380°C for 1000 h. After oxidation tests the coating exhibited high adhesion and fracture resistance. The formation of a glassy phase was not observed.

In the ref. [87] a three-layer EBC coating composed of: $Si/Al_6Si_2O_{13}/Yb_2SiO_5$, sprayed using the APS method was annealed (1300°C/20 h) in air. Despite optimized coating process, vertical cracks appeared in the EBC layers. They were caused by presence of defects and pores in the coating and difference in CTE values between the layers. This affected subsequent behavior of the coating during cyclic oxidation in a steam environment. After 250 cycles, due to the recession phenomenon, evaporation of part of coating material was observed at the edges and in the center of the sample. Cracks were easy diffusion paths for the oxidant, which reacted with Si. It was found that the difference in CTE values between the layers was too large to form an effective EBC coating.

Despite their inferior stability in water vapor, it was decided to focus on disilicates in further studies due to their similar CTE values. It was noted that thermal spraying of yttrium disilicates produces a coating with low porosity, free of vertical cracks [90]. Garcia, Lee, and Sampath [91] studied the effect of different SiO_2 contents in powder mixture used in the atmospheric plasma spraying (APS) process to obtain the desired chemical composition of EBC coating. The authors also noted the effect of phase transformation on the continuity of coating. During thermal spraying by the APS method, an amorphous structure of the coating is formed as a result of very rapid cooling [92]. Its further heat treatment results in the polymorphic transformation, leading to an increase of the coating volume. The SiO_2 coating is part of a system

Table 1. Average CTE values and melting point of rare earth compounds, SiC, Si and Si_3N_4
Tabela 1. Średnie wartości CTE i temperatura topnienia związków pierwiastków ziem rzadkich, SiC, Si i Si_3N_4

Chemical compound	Melting temperature (°C)	CTE, average value (10^{-6} °C^{-1})	Chemical compound	Melting temperature (°C)	CTE, average value (10^{-6} °C^{-1})
Y_2SiO_5	1980	5–6	BSAS	1300	4–5
Er_2SiO_5	1980	5–7, 7–8	BSAS	1300	7–8
Yb_2SiO_5	1950	3.5–4.5, 7–8	mullite	1800	5–6
$Lu_2Si_2O_7$	–	3.8	α-Al_2O_3	2072	6.0–8.4
$Sc_2Si_2O_7 + Sc_2O_3$	1860	5–6	Si	1400	3.5–4.5
$Yb_2Si_2O_7$	1850	4–6	SiC	2545	4.5–5.5
Yb_2O_3	2415	6.8–8.4	Si_3N_4	1875	3–4

Source: [82, p. 3082].

Źródło: [82, s. 3082].

consisting of a SiC/SiC substrate and a silicon interlayer, so the change in its volume is limited, which promotes the phenomenon of "healing" of resulting microcracks [93].

Different thermal spraying methods were used for deposition of EBC coatings: conventional APS [91, 94, 95], SPS (suspention plasma spray) [96], HVOF (high velocity oxy-fuel spraying) [97], VLPPS (very-low pressure plasma spraying) [26] and PS-PVD [95, 98]. High-temperature technologies (APS and SPS) produced coatings with high content of amorphous phase that cracked when cooled to room temperature [99]. HVOF-applied coatings were characterized by a higher amount of crystalline phase, due to the presence of partially molten and unmelted particles and a higher level of porosity [94]. Reduced thermal stresses and increased porosity are responsible for better strain tolerance, making it possible to obtain crack-free coatings. By maintaining the substrate temperature close to 1000°C before spraying in the VLPPS process and using a plasma jet to reduce the cooling rate after deposition, highly crystalline coatings without visible cracks were produced [100]. Actually in EBC coatings development the PS-PVD is one of the most promising deposition technology [101–104]. In further research the possibility of synthesis of new EBC materials during reactive PS-PVD process might decrease it's manufacturing cost [105, 106] and extend their applications.

6. Conclusions

In the case of an aircraft engine, the material and technological solutions used to date (monocrystalline nickel superalloys with TBC coatings, gas cooling) do not allow hot gas temperatures to rise above 1500°C. Further increase is possible only through the development of new material technologies. One of the candidates are SiC/SiC composites with very high thermal stability, creep resistance and high oxidation resistance. However, they are susceptible to CMAS corrosion and the presence of water vapor in the atmosphere, which causes rapid evaporation of formed SiO_2 oxide. For this reason, intensive work is underway on EBC coatings, which should meet many demanding requirements. Even the fulfillment of such demanding conditions does not allow EBC coatings to achieve adequate durability, as they undergo several degradation mechanisms: CMAS corrosion, oxidation, material recession, impact of foreign objects. Over the past five decades, several generations of EBCs have been developed, with mullite coatings as a precursor. Discovery of the recession phenomenon and their rapid destruction associated with it shifted the directions of further research towards BSAS coatings. However, these coatings were also rejected. The reason being the formation of a glassy phase during operation, which significantly shortens their service life at temperatures above 1300°C. Further research led to the development of monosilicates and rare earth disilicates, which form the so-called second generation of EBCs consisting of three layers: a silicon interlayer, a mullite-based interlayer and an outer coating made of rare earth silicates.

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