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Tomasz Sadowski
Przemysław Golewski

Loadings in Thermal Barrier Coatings of Jet Engine Turbine Blades

An Experimental
Research and
Numerical Modeling



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Preface

The book discusses complex loadings of turbine blades and protective layer thermal barrier coating (TBC), under real working airplane jet conditions. They obey both multi-axial mechanical loading and sudden temperature variation during starting and landing of the airplanes. In particular, two types of blades are analyzed: *stationary* and *rotating*, which are widely applied in turbine engines produced by airplane factories.

The numerical modelling, consisting of computational fluid dynamics (CFD) and computational structural mechanics (CSM), requires some basic experimental research, necessary to correct formulation of the turbine blades thermo-mechanical analysis.

The experimental program of research based on the samples with TBC coating was designed for:

- uniaxial tensile tests (UTT),
- 3-point bending tests (3-PB),
- micro-hardness tests.

Before the strength tests, the samples were subjected to aging for different times at the temperature of 1000 °C. The UTT were performed using the ARAMIS optical displacement measurement system and acoustic emission in order to determine the load value at which the TBC cracking is initiated. In order to analyze the level of damage of the protective layer structure the scanning electron microscopy (SEM) observations were carried out. The thermally grown oxide (TGO) layer thickness was measured and the function describing its growth depending on the aging time was determined. The different types of damage which arise as a result of a combination of different aging times and different levels of mechanical stresses were also described. Energy dispersive spectroscopy (EDS) analysis was performed by specifying the content of chemical elements in each layer, which allowed to observe the phenomenon of diffusion due to aging. Micro-hardness test of each layer of the TBC coating became the basis for determining of the elastic properties used in the finite element method (FEM) simulations.

The numerical solution of the thermo-mechanical response of the stationary and rotating turbine blades requires CFD and CSM analyses:

- Thermal loads of *stationary blade* were determined on the basis of CFD simulation, taking into account both the exhaust gas and cooling air flow. The obtained non-uniform temperature fields constitute a basis for determining of the thermal stresses resulting from the difference in thermal expansion coefficients of the blade and ceramic layer materials.
- Numerical calculations were performed for the *rotating moving blade* subjected to a centrifugal and thermal loads force in order to determine the critical places of the blades from which the cracking process initiates.

The obtained results provided the basis for building a more advanced FEM model with application of the extended finite element method (X-FEM) technique. This advanced method allows for introduction of the material cracking to trace trajectory of the major crack in relation to rotational speed of the blade with a TBC layer. The exact analysis of the cracking process is possible by application of the *submodelling technique*, which allowed for separation from the global model a critical fragment of the blade with the highest stress concentration. Introduction of much more dense FEM mesh leads to more precise description of the failure blade process.

The formulated conclusions in this book can be useful for the application of this new methodology in airplane industry.

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Chapter 1

Introduction

Blades, *stationary* (nozzles) and *moving* (turbine), are the most important critical elements of turbine engine, Fig. 1.1. They are exposed to large temperature differences between exhaust and the air that cools them. In this case, the ones under the greatest loads are first degree stationary blades, as they are affected by gases flowing directly from the combustion chamber. The thermal stress occurring in the blade material is the greater, the greater the difference between exhaust gas and cooling air temperatures. Turbine blades that participate in transforming the kinetic energy of exhaust gases into rotational movement energy are additionally loaded with centrifugal force.

Turbine energy efficiency increases with the increase of temperature before the blade assembly. Exhaust gas temperature increase is possible, since aviation fuel combustion temperature is approx. 2300 °C, although it is limited by the strength properties of alloys which blades are made of.

Two methods are used to increase the blade operation temperature:

- cooling,
- application of ceramic Thermal Barrier Coatings (TBCs).

Blade cooling entails significant increase in blade structure complexity and causes losses, as cooling air is drawn from the engine compressor.

The second method has been successfully employed for many years and enables, e.g. higher temperature before the blade assembly, and consequently improved engine efficiency. Protective TBCs remain the object of research, since their damage-related properties have not been fully explored yet. Durability and strength of protective coatings are affected by numerous factors, both related to technology of their deposition, e.g. the effects of substrate roughness, degree of substrate heating, plasma burner power and to operating conditions, e.g. the presence of corrosive environment, erosion, duration of operation, etc.

Literature concerning TBCs can be divided by various criteria. The first is division into the literature containing:

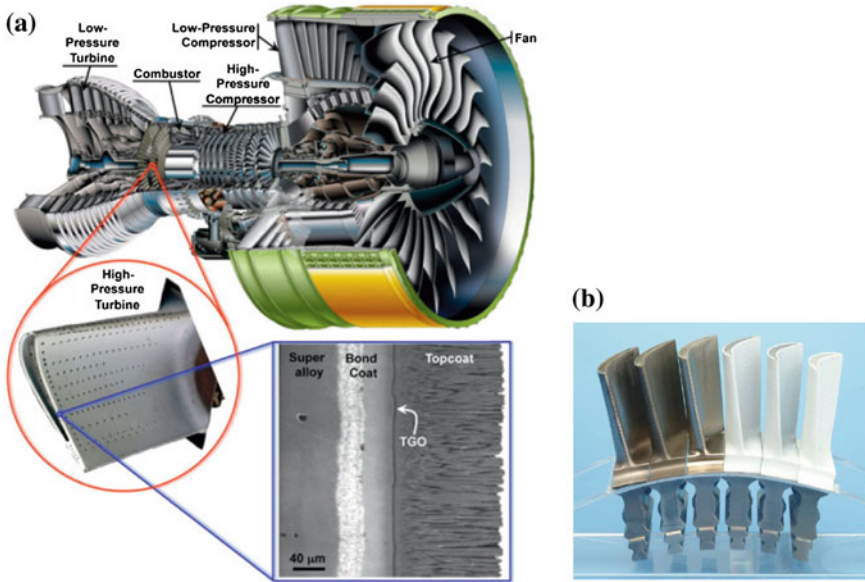


Fig. 1.1 **a** TBCs system, **b** turbine blades without and with TBC

- numerical computer simulation (basing on: FEM—finite element method, FDM—finite difference method, BEM- boundary element method),
- limiting itself to theoretical models and discussions,
- purely experimental studies.

Literature containing computer simulation constitutes approximately 60 % of all published articles. Such division was made for several reasons. The issues of thermal and mechanical loads of turbine engine blades are highly complex due to a number of non-linearities: material, geometry and boundary conditions in the form of non-uniform temperature fields and variable contact. For this reason, it is more beneficial to subject a blade to numerical tests, which will enable not only reduction of costs and acquisition of data, e.g. on stress distribution, but also consideration of varied cases.

By making a deeper distinction into papers containing FEM simulations, we can divide them into those based on 2 dimensional (2D) and 3 dimensional (3D) models. The former are more than twice as numerous, which is related to various difficulties in building 3D models, e.g. generating finite element meshes and greater processing power requirements. In most papers, where 3D models of an actual blade, the end results of simulations are Huber von Mises reduced stress fields and blade proper vibration forms. Frequently, these results are compared to an actual damaged blade.

However, a reliable FEM simulation requires broadly defined material testing, or observation results of blades working under actual conditions. For this reason, the discussed literature can also be divided according to such issues as:

- TBC strength properties tests,
- TBC thermal fatigue tests,
- corrosion, erosion (environmental loads),
- Bond Coat (BC)—Top Coat (TC) contact analysis,
- use of rare earth elements for manufacturing modern TBCs.

Experimental testing of TBCs under thermal and mechanical loads is not an easy matter. The authors propose various shapes of samples and various solutions of holder construction. At times, utilisation of the wrong sample mounting method can lead to errors in results. An example can be the “barb test”. How great a role the workmanship tolerance of the holder itself plays in this case, will be presented in one of the numerical simulations.

However, there are no papers that include material damage due to thermal and mechanical loads in numerical simulations. Therefore, this book will enable filling this gap to some extent. Damage both in micro- and macroscale will be presented.

In particular, the book discusses all issues related to the loads which turbine blades protected by TBC layers on their working surfaces, are subjected to. It includes both:

- a new complex numerical finite element (FE) model of the turbine blades with TBC system consisting of Top Coat (TC—ceramics—yttria stabilised zirconia), Thermally Grown Oxide (TGO layer), BC and substrate,
- original experimental program determining necessary data for calibration of the FE model.

The model allows for detailed description of the gradual degradation of the TBCs systems under active loading thermo-mechanical process of the turbine blades. The proposed model is general and can be applied for any other airplane engines design. The proposed experimental program is enough for estimation of the necessary material data for FE modelling.

Finally, some numerical results are discussed and conclusions are formulated.

Chapter 2

Protective Thermal Barrier Coatings

The goal of using TBCs is, e.g. to reduce thermal conductivity between exhaust gases and the blade material, anti-corrosion protection and increased wear resistance.

A TBC layer must meet the following criteria [1, 2]:

- low thermal conductivity $< 2 \text{ W/(mK)}$,
- high thermal expansion coefficient,
- phase stability between room temperature and operating temperature,
- resistance to sintering at high temperature,
- low Young modulus,
- process properties enabling coating creation, e.g. using Air Plasma Spray (APS) or Electron Beam Physical Vapour Deposition (EB-PVD) [3].

To date, a suitable material that would meet all the above criteria, particularly at temperatures above 1200°C , has not been found.

Currently, TBCs are usually made of zirconium oxide **ZrO₂ stabilised by yttrium oxide Y₂O₃** [1–12]. Zirconium oxide is currently the most popular chemical compound, aside from aluminium oxide Al₂O₃, utilised for production of structural ceramics. It occurs in three polymorphic varieties: monoclinic, tetragonal and regular.

Pure ZrO₂ undergoes phase transition at 1200°C , switching from tetragonal to monoclinic phase during cooling. This phenomenon results in an increase in volume (3–5 %), reduction of porosity and sintering, and consequently a lower tolerance for thermal and mechanical deformations, leading to premature barrier damage. Consequently, production of structural elements made of pure ZrO₂ is impossible.

A solution to this problem is adding stabilising oxides to ZrO_2 , cations of which incorporate themselves in place of zirconium ions. This completely or partially blocks the process of phase transition during material cooling from the sintering temperature. Depending on the application and needs for properties, the following solutions can be distinguished: $\text{Y}_2\text{O}_3\text{--ZrO}_2$, $\text{CeO}_2\text{--ZrO}_2$, MgO--ZrO_2 , ThO--ZrO_2 .

Considering the amount of added stabiliser, either Fully Stabilised Zirconia (FSZ) or Partially Stabilised Zirconia (PSZ)—where a mixture of tetragonal and regular phases occurs—is obtained.

For a specific stabiliser content, e.g. 2–4 %/mol Y_2O_3 and at small grain sizes, ceramics containing almost 100 % tetragonal phase can be obtained. During sintering in temperatures higher than the transformation temperature, the tetragonal grain is enclosed in a matrix. During sinter cooling to room temperature, compressive stresses appear around the tetragonal grain, resulting from the grain's tendency for transformation into the monoclinic form. Depending on the ZrO_2 grain size and matrix strength, these stresses may be relaxed by matrix microcracks forming around the grain, and the grain itself may shift into the monoclinic phase. In the event that the grain is sufficiently small, and the matrix sufficiently strong, the tetragonal grain is super-cooled to room temperature. The described cases lead to increase in cracking resistance and durability of ceramic materials [13].

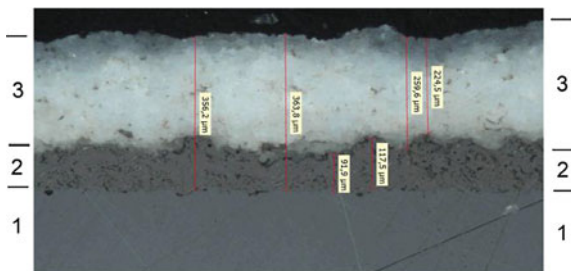
2.1 Structure of TBCs

Protective ceramic coatings are produced using gas phase deposition (e.g. EB-PVD or ASP). The protective coating structure directly depends on the selected method and on process parameters.

A typical coating deposited using the APS method, produced by Pratt and Withney Rzeszów S.A. (Poland—United Technologies Corporation), is composed of two layers (Fig. 2.1):

- bond coat (BC) layer, 50–150 μm thick,
- ceramic layer (top coat—TC), 200–300 μm thick.

Fig. 2.1 Coating created using the APS method. 1 substrate, 2 bond coat, 3 top coat



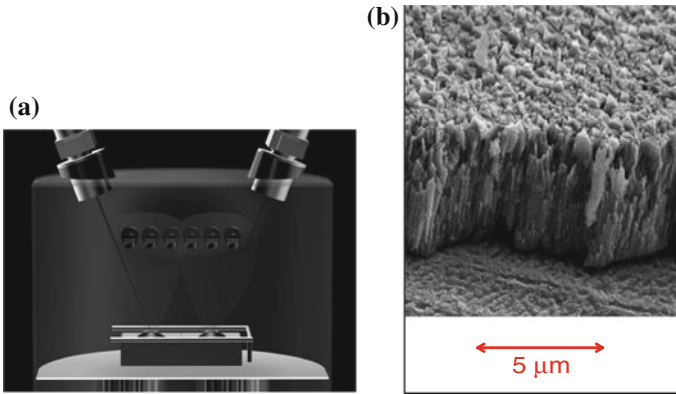


Fig. 2.2 **a** Process chamber with EB guns, crucibles and sample to be coated in the vapour cloud, **b** dendritic structure of a TBC produced by EB-PVD

Figure 2.1 displays an image of a TBC system deposited to a metallic substrate.

A schematic of an EB-PVD TBC system is shown in Fig. 2.2. On the Ni-based superalloy substrate, a BC is deposited, which is an oxidation resistant. A thin layer of alumina, called Thermally Grown Oxide (TGO), is formed on the surface of this BC during the EB-PVD deposition of the TC, which is done under a small vapour pressure of oxygen.

These coatings have a columnar microstructure Fig. 2.2b. The columns are loosely connected, so the ceramic can follow the thermal expansion of the metallic substrate without developing high internal stresses. This behaviour is called “strain tolerance”.

EB-PVD TBCs are more durable, but expensive, relative to the APS TBCs, and they are used primarily in the most severe applications such as turbine blades and vanes.

2.2 Development and Application of New Coating Materials

Promising materials for TBCs are rare earth element-based compounds. To date, several oxide types have been considered for possible application in TBC production:

- pyrochlore-structured oxides,
- fluorite-structured oxides,
- perovskite-structured oxides.

An important group where a new TBC material could be found in is are *rare earth zirconates* [2, 3, 9, 11, 12]. They have the general formula $\text{Ln}_2\text{Zr}_2\text{O}_7$ (Ln—lanthanides such as La, Gd, Eu, Dy). They have an entire range of interesting advantages, such as high melting point, high thermal stability, thermal expansion within the 8×10^{-6} to 11×10^{-6} 1/K range, low thermal conductivity at the level of 1.1–1.5 W/(mK), unique luminescence, radiation stability. They have the pyrochlore or fluorite structures.

Below, several examples of zirconates are presented that may find use in TBCs.

1. Lanthanum zirconate— $\text{La}_2\text{Zr}_2\text{O}_7$ (LZ)—has excellent thermal stability and chemical resistance, high melting point of 2700 °C. It has a significant advantage of low thermal conductivity equalling 1.56 W/(mK); for comparison, this value for YSZ is 2.5 W/(mK). Furthermore, there are no phase transformations within the range from ambient temperature to operating temperature. Its main drawback is low thermal expansion in comparison with blade material, equalling 9.1×10^{-6} 1/K, resulting in occurrence of thermal stresses. Another disadvantage is lack of commercial availability and time-consuming production. The latter disadvantage could be eliminated, however, as in paper [9], the authors proposed an energy-efficient and fast method for producing $\text{La}_2\text{Zr}_2\text{O}_7$. The entire coating deposition process can be divided into three stages:

- *Melting by plasma.* This consists in La_2O_3 and ZrO_2 granules being placed in a graphite cylinder that is cooled and constitutes the anode. The cathode is a cooled graphite rod. The device power is 5 kW and is used for melting the granules using plasma, and consequently mixing them, while maintaining minimal porosity.
- *Spheroidisation using plasma.* After cooling, the melted mixture is ground in a ball mill using zirconium balls. Spheroidisation is also conducted in a plasma reactor with 40 kW power. The material in spherical form leaves the plasma stream and passes a 300 mm distance, ending in a polished steel container.
- *Plasma spraying.* Powder in spherical form is sieved in order to obtain 10–45 mm particles. Deposition is performed using a plasma stream in a device with 40 kW power.

The paper [9] also analyses microscopic images for various powers of the plasma reactor. The resulting degree of spheroidisation ranges from approx. 48 % for 21 kW power to 90 % for 29 kW.

To summarise—the above method of lanthanum zirconate production is quick, simple and efficient. Melting 30 g of granules takes 10 min. The optimum spheroidisation power, for which efficiency equals 78 %, is 27 kW. While greater efficiency is achieved at a higher power of 29 kW, some of the powder is vapourised in the process.

It also bears mentioning that research is being conducted on the effects of additions to lanthanum zirconate, such as Gd_2O_3 , Yb_2O_3 , Sm_2O_3 concerning improvement of thermo-mechanical properties of coating materials [2, 4, 5].

2. An in-depth analysis of samarium oxide addition was performed by the authors of paper [5]. The formula of the material was $(\text{Sm}_{1-x}\text{La}_x)_2\text{Zr}_2\text{O}_7$ for $x = 0, 0.25, 0.5, 0.75$ and 1. Obtaining such materials required a temperature of 1600 °C and time of approximately 10 h, using such oxides as: Sm_2O_3 , La_2O_3 and ZrO_2 . The most beneficial effect was achieved for $x = 0.5$, i.e. the $(\text{Sm}_{0.5}\text{La}_{0.5})_2\text{Zr}_2\text{O}_7$ material, for which thermal conductivity remains constant in the entire temperature range and is approximately 1 W/(mK). This new composite could possibly replace YSZ, particularly if the technology presented in [9] is utilised.
3. CeO_2 was considered as a substitute for ZrO_2 , since material containing cerium dioxide generally have a higher thermal expansion coefficient [14, 15]. Therefore, another new material possible to be used as TBC is $\text{La}_2\text{Ce}_2\text{O}_7$ (LC). It is a metallic solution of La_2O_3 in CeO_2 , with fluorite structure. Main advantages of LC are low thermal conductivity and no phase transformation within the range from room temperature to 1400 °C. However, thermal expansion drops rapidly for the 200–400 °C, and furthermore, LC reacts with the $\alpha\text{-Al}_2\text{O}_3$ phase at high temperatures. The result of such behaviour is low number of heating—cooling cycles that such coating can transfer.
4. If cerium or zirconium is replaced with titanium and aluminium, the result will be another material considered in paper [12] $\text{LaTi}_2\text{Al}_9\text{O}_{10}$ (LTA), which can replace YSZ for applications up to 1300 °C. LTA is obtained through synthesising La_2O_3 , TiO_2 and Al_2O_3 oxides at 1500 °C for 24 h. Its stability is perfect up to 1600 °C, thermal conductivity at approximately 1–1.3 W/(mK) within the 300–1500 °C range, and the thermal expansion coefficient value is 8×10 to 11.2×10 (1/K) for the 200–1400 °C range. Microhardness of both LTA and YSZ is the same and equals approximately 7 GPa, however, cracking resistance of LTA is lower.
5. In study [1], the authors performed a similar synthesis, although barium carbonate BaCO_3 was used instead of Al_2O_3 . The synthesis was also conducted at 1500 °C for 48 h in plasma atmosphere. The result is a perovskite-structured material $\text{BaLa}_2\text{Ti}_3\text{O}_{10}$ (BLT). Instead of lanthanum, other oxides containing rare earth elements, such as Sm, Nd, Pr can be synthesised. BLT maintains phase stability within the range from room temperature to 1400 °C, and sintering resistance up to 1500 °C. It exhibits a linear increase in thermal expansion during temperature rise up to 1200 °C. Thermal expansion coefficient is within the 1×10 to 12.5×10 1/K range, and such values are comparable to 7YSZ. Its porosity is 13 %, while microhardness is within the 3.9–4.5 GPa range. BLT thermal conductivity at 1200 °C equals 0.7 W/(mK), which is particularly beneficent for TBC applications. Tests have demonstrated that it survives up to 1100 cycles of heating to 1100 °C and cooling to ambient temperature, while material destruction occurred by way of TGO layer cracking. For YSZ, a result of 1000 cycles before the appearance of first cracks was achieved.
6. Barium carbonate is also used in another synthesis using yttrium oxide [8]. Synthesis of BaCO_3 and Y_2O_3 , two powders mixed together, was conducted at 1000 °C for 20 h in air. The product was BaY_2O_4 (BLT). Next, everything was crushed and sieved. Its thermal conductivity at room temperature is 3.9 W/(mK)

and decreases to 1.9 W/(mK) at 850 °C. In order for the material to be usable as TBC, its thermal conductivity must be lower than 2 W/(mK) within the entire operating range. The tested material does not fully meet this condition. Strontium was also considered instead of barium, although the results achieved here were even worse and thermal conductivity at 1000 °C was as much as 3.3 W/(mK).

7. Strontium compound with zirconium and oxide SrZrO_3 doped with Yb_2O_3 and Gd_2O_3 was also considered as a new composite for replacing YSZ [7]. Powders used for synthesis were: SrCO_3 , ZrO_2 , Yb_2O_3 , Gd_2O_3 . First they were ground in a ball mill and—after drying—roasted at 1400 °C. Subsequently they were transferred to the ball mill again. The synthesis products have the following formulas: $\text{Sr}(\text{Zr}_{0.9}\text{Yb}_{0.1})\text{O}_{2.95}$ and $\text{Sr}(\text{Zr}_{0.8}\text{Gd}_{0.2})\text{O}_{2.9}$. Both additions result in decreasing the thermal conductivity of SrZrO_3 . The addition of Yb_2O_3 has a significant effect, since it causes a decrease in thermal conductivity, compared to YSZ, by approx. 20 %. Using the additions mentioned above, similar mechanical properties are achieved as for YSZ. The results of cycle testing definitely disqualify the gadolinium oxide addition, since only 13 cycles are achieved, while doping ytterbium in the form of oxide—as many as 806 cycles.

2.3 Conclusions

To date, there is no clear answer to what material can be used as a replacement for YSZ to increase blade operation temperature and increase engine power. There are several composite materials that could replace YSZ, such as: $\text{La}_2\text{Zr}_2\text{O}_7$, $\text{LaTi}_2\text{Al}_9\text{O}_{10}$ or $\text{Sr}(\text{Zr}_{0.9}\text{Yb}_{0.1})\text{O}_{2.95}$. However, there are currently no experimental results confirming their properties when used under actual operating conditions.

Synthesis technologies mentioned in papers [1, 5, 7, 8], for materials based on rare earth elements require high temperatures of 1000–1600 °C long process duration, 24–48 h. As an alternative, paper [9] presents a plasma-based technology, which significantly simplifies and shortens the process.

Very good results are achieved for hybrid coatings: metal–BC–TC–1–TC–2. Further works should focus on such materials as $\text{La}_2\text{Ce}_2\text{O}_7/8\text{YSZ}$ and $\text{Sr}(\text{Zr}_{0.9}\text{Yb}_{0.1})\text{O}_{2.95}/\text{YSZ}$, which surpass typical YSZ coatings with their properties.

References

1. Hongbo G, Hongju Z, Guohui M, Shengkai G (2009) Thermo-physical and thermal cycling properties of plasma sprayed $\text{BaLa}_2\text{Ti}_3\text{O}_{10}$ coating as potential thermal barrier materials. *Surf Coat Technol* 204:691–696
2. Liu ZG, Ouyang JH, Zhou Y (2009) Heat capacities and derived thermodynamic functions of neodymium–gadolinium zirconates from 298.15 to 1050 K. *J Alloys and Compd* 475:21–24

3. Fenech J, Dalbin M, Barnabe A, Bonino JP, Ansart F (2001) Sol-gel processing and characterization of (RE-Y)-zirconia powders for thermal barrier coatings. *Powder Technol* 208:480–487
4. Hongming Z, Danqing Y (2008) Effect of rare earth doping on thermo-physical properties of lanthanum zirconate ceramic for thermal barrier coatings. *J Rare Earths* 26:770–774
5. Hongsong Z, Kun P, Qiang X, Fuchi W, Ling L (2009) Thermal conductivity of $(\text{Sm}_{1-x}\text{La}_x)_2\text{Zr}_2\text{O}_7$ ($x = 0, 0.25, 0.5, 0.75$ and 1) oxides for advanced thermal barrier coatings. *J Rare Earths* 27:222
6. Ma W, Dong H, Guo H, Gong P, Zheng X (2010) Thermal cycling behavior of $\text{La}_2\text{Ce}_2\text{O}_7$ /8YSZ double-ceramic-layer thermal barrier coatings prepared by atmospheric plasma spraying. *Surf Coat Technol* 204:3366–3370
7. Ma W, Macka D, Malzbender J, Vaßen R, Stover D (2008) Yb_2O_3 and Gd_2O_3 doped strontium zirconate for thermal barrier coatings. *J Eur Ceramic Soc* 28:3071–3081
8. Maekawa T, Kurosaki K, Yamanaka P (2007) Thermophysical properties of BaY_2O_4 : A new candidate material for thermal barrier coatings. *Mater Lett* 61:2303–2306
9. Ramachandran CP, Balasubramanian V, Ananthapadmanabhan PV (2012) Synthesis, spheroidization and spray deposition of lanthanum zirconate using thermal plasma process. *Surf Coat Technol* 206:3017–3035
10. Tamura M, Takahashi M, Ishii J, Suzuki K, Sato M, Shimomura K (1999) Multilayered thermal barrier coating for land-based gas turbines. *J Therm Spray Technol* 8:68–72
11. Wan C, Qu Z, Du A, Pan W (2009) Influence of B site substituent Ti on the structure and thermophysical properties of $\text{A}_2\text{B}_2\text{O}_7$ -type pyrochlore $\text{Gd}_2\text{Zr}_2\text{O}_7$. *Acta Materialia* 57:4782–4789
12. Xie X, Guoa H, Gong P, Xua H (2011) Lanthanum–titanium–aluminum oxide: a novel thermal barrier coating material for applications at 1300 °C. *J Eur Ceramic Soc* 31:1677–1683
13. Niezgoda T, Małachowski J, Szymczyk W (2005) Numerical modelling of ceramic microstructure. WNT, Warszawa (in Polish)
14. Chen JP, Duh JG (2001) Indentation behavior and Young's modulus evaluation in electroless Ni modified CrN coating on mild steel. *Surf Coat Technol* 139:6–13
15. Chen X, Hutchinson JW (2002) Particle impact on metal substrates with application to foreign object damage to aircraft engines. *J Mech Phys Solids* 50:2669–2690

Chapter 3

Thermal Loads

Thermal loads of combustion turbine blades can only be assessed by analysing their temperature fields. Knowledge of temperature fields enables determining the maximum temperature and temperature gradient values that decide thermal stresses and deformations. Both exceeding the acceptable temperatures and stresses, and excessive deformations can lead to damage, premature wearing out or incorrect engine operation. Temperature field analysis enables calculating local values and densities of heat fluxes, i.e. performing a complete analysis of heat flow.

Under stationary operating conditions, steady temperature fields appear in sections of the turbine, leading to steady state heat stresses. During engine start, after closing fuel flow or after engine stop, and when working conditions alter, temperatures in individual sections of the turbine change. If thermal loads are not determined, there may occur much higher, dangerous temperature gradient values, and in completely different parts of the engine than under stationary conditions.

Therefore, correct determination of acceptable working medium temperatures before the turbine's blade assembly requires knowledge of steady state temperature distributions in the most thermally loaded parts of the turbine, i.e. in the stator blades, rotor blades, turbine disc and turbine case. Studying transient temperature fields is necessary for rational design and operation of turbine engines (Fig. 3.1).

3.1 Numerical Methods—Application of Finite Elements Method (FEM) [1, 2]

As a result of the TBC structure and blade shape being highly complex, analytical solution consisting in determining the temperature field with transient heat flow states is a complex mathematical problem. Consequently, aside from precise analytical equations, another solution is also employed using the FEM or the FED in order to determine the temperature distribution in the entire volume.

Fig. 3.1 PZL-10 W engine blade

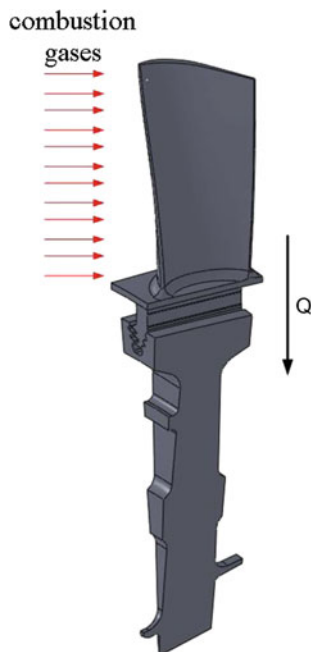
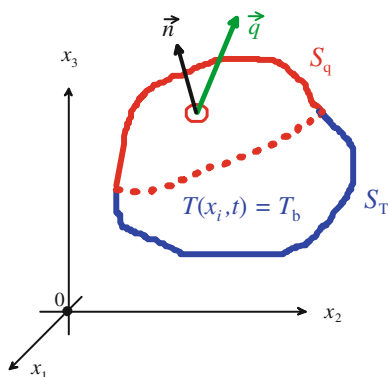


Fig. 3.2 Boundary conditions for heat conduction problem



We will investigate the thermo-mechanical response of the structural element of the jet turbine engine. In the general case, the structural element occupying a space with volume V , surrounded by a surface S in an $\{x_i\}$ ($i = 1, 2, 3$) axis system of a spatial coordinate system (Fig. 3.2) will be considered.

The essence of using FEM for solving field theory problems consists in dividing the examined volume into a finite number of subdomains, i.e. finite elements (FE) creating the FE mesh. The set of basic equations characterising analysed thermo-mechanical problem is solved in approximated way to find the values of the function sought in the FE nodal points.

Discretisation of a geometric area in FEM can be achieved using FE of various kind including curve-edged elements. The use of more geometrically-complex elements does not create formal problems and most commonly neither does it lead to greater numerical difficulties. At the same time, the possibility of using varied elements, including curve-shaped ones, enables good approximation of even complex boundaries of geometric areas.

The basic equations describing the phenomenon of undetermined thermal load in a flexible and anisotropic material are as follows:

- *Fourier's law*

$$q_i = -k_{ij}T_{,j}, \quad (3.1)$$

where

q_i components of the heat flux vector $\vec{q}(x_i, t)$,
 k_{ij} components of the heat conductivity tensor $\mathbf{k}(x_i, t)$,
 $T_{,j}(x_i, t) = \partial T / \partial x_j$ temperature gradient.

- *heat flow equation*

$$q_{i,i} + Q = \rho c_v \frac{\partial T}{\partial t} \quad (3.2)$$

where

Q heat flow speed related to unit volume,
 $\partial T / \partial t$ time derivative of temperature field $T(x_i, t)$,
 $\rho(x_i, t)$ and $c_v(x_i, t)$ are, respectively: density and specific heat.

By combining Eqs. (3.1) and (3.2), the basic equation describing temperature diffusion during heat flow is obtained

$$\left(k_{ij} \frac{\partial T}{\partial x_j} \right)_{,i} = -Q + \rho c_v \frac{\partial T}{\partial t} \quad (3.3)$$

Equation (3.3) is a general expression describing transient heat transfer problem. All properties of the material are considered as functions of space $\{x_i\}$ and time t , and anisotropy of the material is taken into account. In the simplest case, material properties do not have to depend on time t e.g. $\rho(x_i)$, $c_v(x_i)$, $\mathbf{k}(x_i)$. Furthermore, the thermal conductivity tensor is in the general case considered as symmetric $k_{ij} = k_{ji}$. If the material is anisotropic, heat flow does not necessarily have to agree with the temperature gradient direction. For isotropic materials, thermal conductivity is described as a scalar $k = (1/3)k_{ij}\delta_{ij}$.

The thermal conductivity Eq. (3.3) must be solved with the following initial boundary conditions taken into account:

- by stating the temperature distribution for $t = 0$,

$$T(x_i, 0) = T_0(x_i, 0) \quad (3.4)$$

- by determining the heat flow flux on surface S_q

$$q_i n_i = h_b \quad (3.5)$$

- by determining the temperature distribution on surface S_T

$$T(x_i, t) = T_b \quad (3.6)$$

where: $S_q + S_T = S$, $\vec{n}$ —unit vector normal to surface S .

Equation (3.3) can be solved:

- analytically, using the perturbation method, using the Laplace or Fourier transform, or using a Green's function,
- numerically—by using the FEM or FDM.

Further considerations focus on numerical approaches to solving Eq. (3.3). Considering variational formulations of Eq. (3.3), it is assumed that a material or structural element is subject to temperature changes δT . It is assumed that δT meets the previously stated boundary conditions. Next, after integrating with respect to the entire material volume, we receive the following:

$$\int_V \left[\rho c_v \frac{\partial T}{\partial t} - \left(k_{ij} \frac{\partial T}{\partial x_j} \right)_{,i} - Q \right] \delta T dV = 0 \quad (3.7)$$

After applying Green's formula, we receive:

$$\int_V \left[\left(\rho c_v \frac{\partial T}{\partial t} - Q \right) \delta T - (q_i \delta T)_{,i} \right] dV + \int_{S_q} h_b \delta T dS = 0 \quad (3.8)$$

The above equation can be solved using the FEM. In order to do it, the whole material must be divided into a finite number of elements connected at nodes. When shape functions in matrix form $[N_e]$ and vector $\{T\}$, defining temperature values at nodes are available, the temperature field $T(x_i, t)$ for every element “ e ” can be determined:

$$T(x_i, t) = N_e \{T\}. \quad (3.9)$$

Using Eq. (3.9), the temperature gradient can be determined in the following form

$$\left\{ \begin{array}{c} \frac{\partial T}{\partial x_1} \\ \frac{\partial T}{\partial x_2} \\ \frac{\partial T}{\partial x_3} \end{array} \right\} = [B_e]\{T\} \quad (3.10)$$

where

$$[B_e] = [\nabla][N_e]$$

$[\nabla(\dots)] = [\partial(\dots)/\partial x_1 \quad \partial(\dots)/\partial x_2 \quad \partial(\dots)/\partial x_3]^T$ is the differential operator of quantity (...).

Fourier's law is described by equation

$$\{q\} = \left\{ \begin{array}{c} q_1 \\ q_2 \\ q_3 \end{array} \right\} = -[k_{ij}][B_e]\{T\} \quad (3.11)$$

$[k_{ij}]$ thermal conductivity matrix.

By introducing (3.10)–(3.11) to (3.9), we receive equations describing heat flow in the following form

$$[C]\{\dot{T}\} + [K]\{T\} = \{\hat{q}\} \quad (3.12)$$

where $\{\dot{T}\}$ means derivative of time T , and

$$[C] = \int_{\Omega} \rho c_v [N_e]^T [N_e] d\Omega, \quad (3.13)$$

$$[K] = \int_{\Omega} [B_e]^T [k] [B_e] d\Omega, \quad (3.14)$$

$$\{\hat{q}\} = - \int_S [N_e]^T h_b dS + \int_{\Omega} Q [N_e]^T d\Omega, \quad (3.15)$$

Ω space occupied by finite elements approximating the structural element,

S boundary surface.

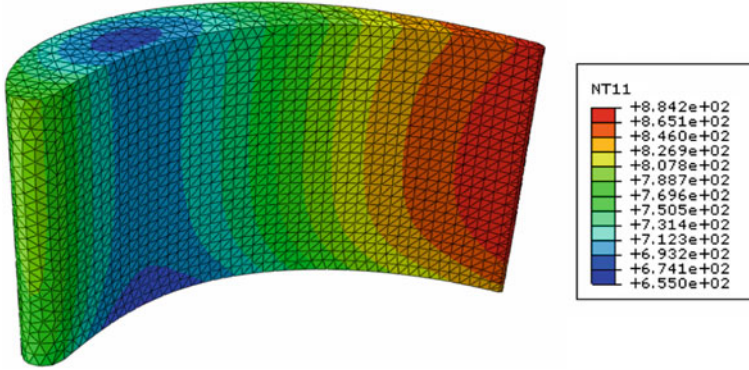


Fig. 3.3 Temperature distribution in a blade

Figure 3.3 presents the temperature distribution in the entire volume of a turbine engine blade fragment, for a transient state. Temperature in the blade ranges from 655 °C in the middle section, with the highest thickness to 884.2 °C at the trailing edge. Additionally, heat outflow to the blade rim was taken into account, and consequently a lack of symmetry in temperature fields can be noted, when viewing the top and bottom parts of a blade.

Such detailed information on temperature distributions can be provided neither by experimental measurement methods utilising thermo-elements, nor the analogue method. Distribution of temperature in the structural element volume is necessary in order to determine the effort of the blade material and the TBC.

3.2 Deformation and Stress in Structural Elements, Caused by Thermal Loads [1, 2]

Thermoelasticity is a field where mutual interactions of deformation fields and temperature fields are studied by way of fundamental thermodynamics laws.

With temperature fields $T(x_m, t)$ determined for the entire sample or structural element (e.g. Fig. 3.3), it is possible to determine thermal stresses $\bar{\sigma}_{ij}(x_i, T, t)$. Differential equations governing thermoelasticity are as follows:

- *equation of motion:*

$$\bar{\sigma}_{ij,j} + \rho f_i = \rho \ddot{u}_i \text{ in volume } V, \quad (3.16)$$

where:

f_i are components of body forces per unit of mass,

$\ddot{u}$ components of acceleration vector

In quasi-static problems we have equilibrium equations:

$$\bar{\sigma}_{ij,j} + \rho f_i = 0 \text{ in volume } V. \quad (3.17)$$

- *Duhamel–Neumann’s constitutive equation:*

$$\bar{\sigma}_{ij} = \bar{C}_{ijkl}\bar{e}_{kl} - \bar{\beta}_{ij}(T - T_0), \quad (3.18)$$

or

$$\bar{e}_{ij} = \bar{S}_{ijkl}\bar{\sigma}_{kl} + \bar{\alpha}_{ij}(T - T_0), \quad (3.19)$$

where: $\bar{\sigma}_{ij}$ and $\bar{e}_{ij}$ are mean symmetric tensors of stresses and deformations.

$\bar{C}_{ijkl}(x_m, T)$ and $\bar{S}_{ijkl}(x_m, T)$ are components of elasticity tensors, mean or equivalent to stiffness and compliance.

In the general case, the TBC composite material is non-homogeneous and anisotropic and its properties may depend on position in space and temperature T , i.e. $\bar{\alpha}_{ij}(x_m, T)$ and $\bar{\beta}_{ij}(x_m, T)$. $\bar{\alpha}_{ij}$ and $\bar{\beta}_{ij}$ here are second order symmetric tensors describing anisotropy and non-uniform thermal properties of the material.

T_0 in (3.19) is an initial temperature of the thermal process,

- *thermal conductivity equation in the most general form, including thermo-mechanical coupling:*

$$\left(k_{ij} \frac{\partial T}{\partial x_j} \right)_{,i} = -Q + \rho c_v \frac{\partial T}{\partial t} + T_0 \bar{\beta}_{ij} \dot{\bar{e}}_{ij}, \quad (3.20)$$

where $\dot{\bar{e}}_{ij}$ denotes time derivative of the mean strain tensor $\bar{e}_{ij}$.

A simpler version of (3.20), without coupling effect, is described by Eq. (3.3). The equation of motion can be expressed in relation to components of displacement vector u_i using the constitutive Eq. (3.19) and definition of small deformations:

$$\frac{1}{2} \left[\bar{C}_{ijkl,j} (u_{k,l} + u_{l,k}) + \bar{C}_{ijkl} (u_{k,l} + u_{l,k})_{,j} \right] + \rho f_i = \rho \ddot{u}_i + \bar{\beta}_{ij} T_{,j} + \bar{\beta}_{ij,j} T \quad (3.21)$$

Equations (3.20) and (3.21) constitute a system of equations used for finding four function unknowns: u_1, u_2, u_3 and T . The state of stress $\bar{\sigma}_{ij}(x_m, T)$ can be determined using the Duhamel–Neumann’s constitutive Eq. (3.18).

Thermal and mechanical properties of an isotropic and non-homogeneous elastic composite material with perfect connection at the phase boundary are described by:

- Young’s modulus $\bar{E}(x_m, T)$
- Poisson number $\bar{\nu}(x_m, T)$
- thermal properties of the material: $\bar{\alpha}(x_m, T), \bar{\beta}(x_m, T)$.

3.3 Numerical Analysis of Temperature Fields in Critical Elements of Turbo-Engines by CFD (Computational Fluid Dynamics) with Application of FLUENT Program

In order to determine the thermal loads, aside from material data, temperature fields are needed as well. During operation, turbine engine blades heat in a non-uniform manner, and the entire problem is additionally made difficult by the complex geometric shape of the blade. For this reason, temperature fields in turbine engine blades are obtained using computer simulations [3–5]. One such program is FLUENT, included in the ANSYS software.

Generally, each simulation comprises three stages: pre-processing, calculations (use of solver) and post-processing.

The first step of *pre-processing* is geometry preparation. It can either be done directly in the ANSYS environment using the Design Modeler module, or imported from another CAD system, e.g. SolidWorks. If a real blade model is available, 3D scanning can be used, and subsequently, after geometry processing, only a selected fragment may be subjected to simulation (Fig. 3.4).

Blade geometry must additionally be extended to include at least volume that will constitute a channel through which exhaust is going to flow. It is created as a normal solid. If cooling channels are present in the considered blade, an additional solid model must also be created for air volume. During the end stage of model preparation, three or more solid models must be combined (Fig. 3.5). They will be automatically recognised in the program during further pre-processing steps.

Before a solution is achieved, discretisation must be performed in the specific geometric system (Fig. 3.6). In a large simplification, this step consists in creating a numerical mesh, i.e. dividing the studied continuous area into a finite set of geometric primitives, that will subsequently be used to determine the nonlinear Navier–Stokes equations solution:

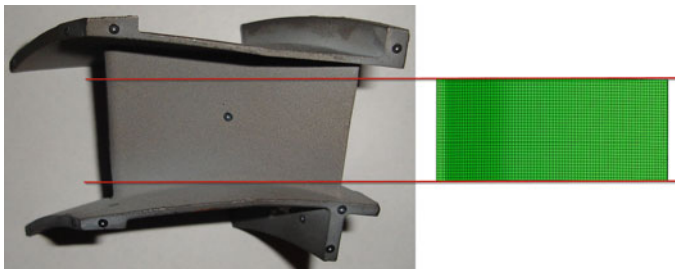


Fig. 3.4 Actual steering blade of the PZL-10 W engine together with an isolated fragment participating in simulations

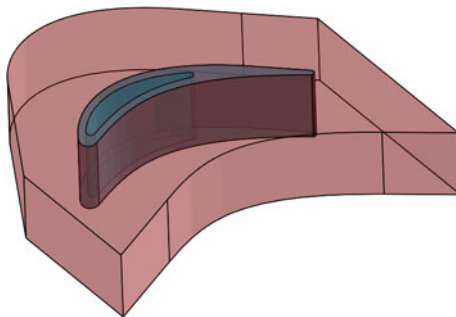


Fig. 3.5 Model construction for CFD simulations

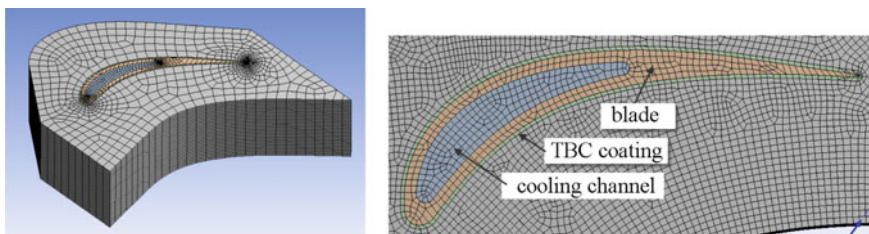


Fig. 3.6 Finite element mesh

$$\left[\frac{\partial}{\partial t} + v_j \frac{\partial}{\partial x_j} - \varpi \frac{\partial^2}{\partial x_j \partial x_j} \right] v_i = - \frac{\partial w}{\partial x_j} + g_i, \quad (3.22)$$

where v_i are flow velocity vector components, ϖ is the kinematic viscosity, w —is the specific (per unit mass) thermodynamic work (internal source), whereas g_i —represents body acceleration per unit mass (external source). For our case of flow, fluid over the blade surfaces the nonlinear Navier–Stokes equations allow for making of turbulent flow analysis (time dependent chaotic behaviour) with e.g. k – ε model (turbulence kinetic energy model).

Mesh creation boils down to dividing the object into spatial solids (tetrahedrons, cubes) which have common points called nodes.

Two primary types of FE meshes are distinguished in CFD calculation methods: structural and non-structural. Non-structural meshes are used more commonly due to complex geometry and their non-uniform density. Mesh density should be greater in the area of expected high flow gradients, secondary and turbulent flows. The greater the mesh density, the greater calculation precision is expected, although

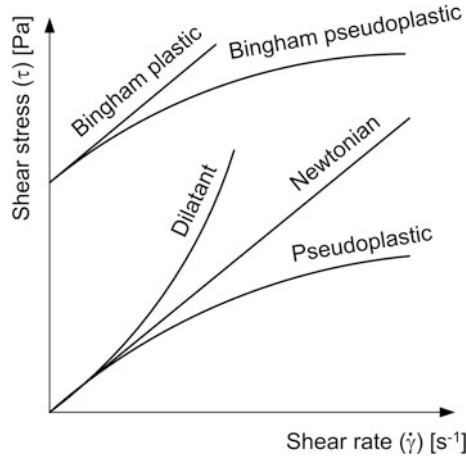


Fig. 3.7 Newtonian or no-Newtonian fluid behaviour

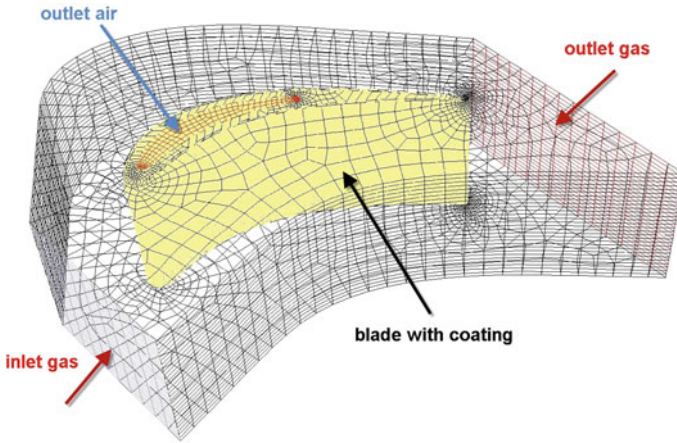


Fig. 3.8 Indication of boundary conditions

it is paid for with an increase in computer processing power demand, which increases the calculation time.

Another important pre-processing phase that significantly affects the obtained results is the definition of fluid properties, and particularly specification whether the fluid is Newtonian or non-Newtonian, Fig. 3.7. In the case of non-Newtonian fluids, the rheological equation describing the studied medium must be defined.

The pre-processing stage concludes in specifying the boundary conditions in space and time domain (initial conditions). It consists in indicating the surfaces limiting the calculation area and arbitrarily assuming the flow conditions in these

places (Fig. 3.8). In order to define the boundary or initial conditions, their nature at the inlet, outlet and wall must be defined.

The inlet is in other words a place (fragment of a boundary) where fluid inflow occurs. Speed or pressure field is defined here, most commonly it is assumed to be flat, unformed.

The outlet is a boundary of an area where outflow of the medium occurs. Most commonly a zero (reference) value of pressure is defined.

A wall means a surface impermeable for flow, equivalent to rigid walls. Here, there are several options available. First, walls can have a pre-set temperature, or they may be adiabatic, lack of slide of the fluid along structural elements may also be assumed.

The second step of numerical analysis is referred to as *processing*. It is the proper part of the calculation endeavour, where problem is solved numerically using the solver, after it has read pre-processing data concerning the studied geometry of the object and the boundary conditions.

Post-processing is the last step of flow modelling. Its aim is to analyse and present the obtained data, and process them into a graphical form. Visualisation of simulation results involves creating charts, histograms, contour maps, isolines or animations.

Figure 3.9 presents temperature maps obtained by simulating the effects of exhaust gases on a blade with a cooling hole. Due to the fact that the model comprised several separate parts, each of them may be presented separately in the visualisation.

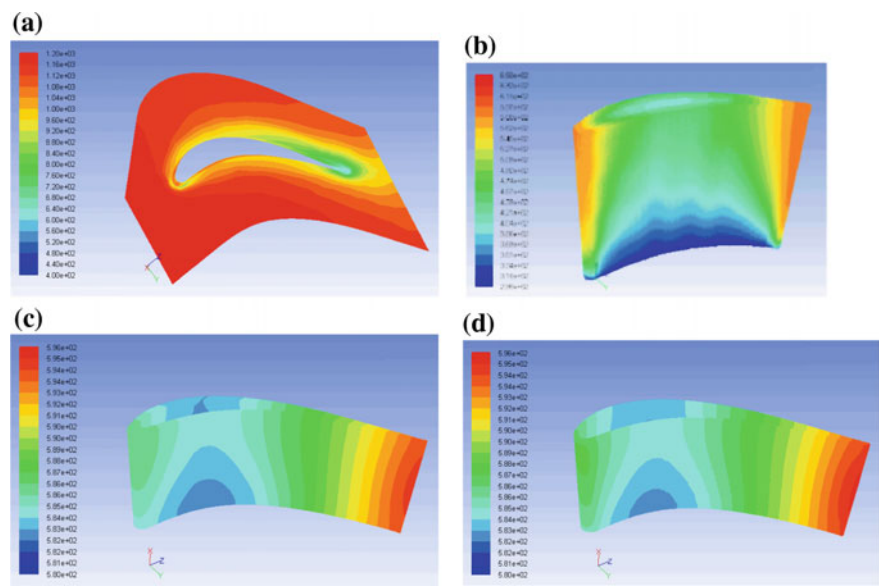


Fig. 3.9 Temperature maps **a** exhaust, **b** air, **c** blade and **d** coating

An important stage after conducting CFD simulations is temperature mapping. This process consists in pre-importing the same geometric model of a blade that was used in the FLUENT program to the ABAQUS program. In ABAQUS, a finite element mesh is generated, after which an .inp file is created. When in the volume Fluid Structure Interaction (FSI) Mapping window (FLUENT), temperatures are mapped onto the generated mesh (.inp file) after selecting ABAQUS as the output file type. The new .inp file must be recalculated in ABAQUS in order to acquire an .odb results file with the temperatures. Indicate the path to the .odb file in ABAQUS in the Predefined Field position as initial temperatures when studying thermal shocks and, consequently, when determining stresses.

3.4 Conclusions

In the case of turbine engine blades, in order to obtain temperature fields in the entire volume, it is necessary to perform numerical flow simulations. Current development and advancement degree of programs designed for FEM enables exporting the obtained results as temperature fields directly into structural simulations, and as a result, determining material effort. Additionally, there is the two way FSI simulation, where both the fluid affects the solid, and the solid can affect fluid flow. The next step in development will be making optimisation of both geometric parameters of the solid and of flow parameters more common.

References

1. Sadowski T, Ataya P, Nakonieczny K (2009) Thermal analysis of layered FGM cylindrical plate subjected to sudden cooling process at one side—comparison of two applied methods for problem solution. *Comput Mater Sci* 45:624–632
2. Sadowski T (2009) Non-symmetric thermal shock in ceramic matrix composite (CMC) material. *Lect Notes Compos Mater Solid Mech Appl* 154:99–148
3. Guo PQ, Mumm DR, Karlsson AM, Kagawa Y (2005) Measurement of interfacial shear mechanical properties in thermal barrier coating systems by a barb pullout method. *Scripta Materialia* 53:1043–1048
4. Hager CH Jr, Sanders J, Sharma P, Voevodin A (2007) Gross slip fretting wear of CrCN, TiAlN, Ni, and CuNiIn coatings on Ti₆Al₄V interfaces. *Wear* 263:430–443
5. Hejwowski T, Weroński A (2000) The production of the wear—resistant coatings. The heat applied coatings on elements of internal combustion engines. Lublin University of Technology Press, Lublin (in Polish)

Chapter 4

Mechanical Loads

Mechanical loads affecting turbine engine blades include: loads caused by static and dynamic interaction of the flowing medium with the profiled part of the blade, body loads caused by centrifugal forces, and loads caused by elastic vibrations of blades and the entire rotor. During work, the following stresses occur in blades of turbines and axial compressors:

- Tensile—caused by centrifugal forces of rotating blade and shroud bodies,
- Bending—from the medium pressure on the profiled part,
- Bending—from centrifugal forces affecting the rotating blade body,
- Tangent—from torsional moments of forces, caused by the flowing medium,
- Tangent—from torsional moments of blade body forces,
- Bending—caused by perpendicular vibrations of the blade,
- Tangent to torsional vibrations of the blade's working part.

Normal resulting stresses, in any transverse cross section of the blade, are calculated as the algebraic sum of normal component stresses. Strength calculations seek places where the greatest normal or reduced stresses are located.

In order to obtain the values of reduced stresses originating from such a complex system of loads, it is necessary to use numerical methods.

4.1 Preparation of Model for Simulation

PZL-10 W engine propulsion turbine (Fig. 4.1a) comprises 51 blades (Fig. 4.1d). Blades are fixed to the disc using fir tree slots.

Due to the symmetry, further analysis was performed for one blade and a section of the disc (Fig. 4.1b). In order to reduce the calculation time, a major portion of the disc below the fir tree slots was cut off. The material used for production of the

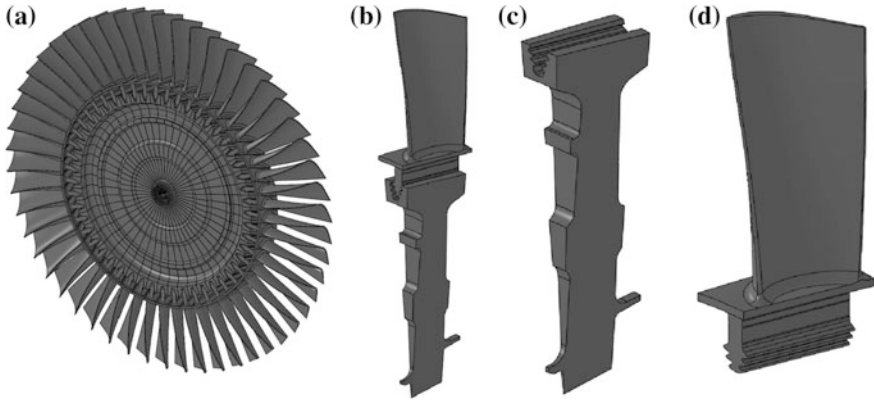


Fig. 4.1 3D model

above-mentioned blade is ŽS6U. The simulation included an elasto-plastic description of the material, together with changes that occur under the effects of temperature. The elastic material behaviour is described by (3.17). The Huber-von Mises plasticity yield criterion was applied to obtain plastic strain increments in the following form:

$$f(\sigma_{ij}, \sigma_y) = J_2(\sigma_{ij}) - (1/3)(\sigma_y)^2 = 0, \quad (4.1)$$

where $J_2(\sigma_{ij})$ —is the second deviatoric stress invariant, σ_y —is the yield stress. The corresponding flow rule is given by

$$d\varepsilon_{ij}^p = d\lambda \frac{\partial f}{\partial \sigma_{ij}} = d\lambda s_{ij}, \quad (4.2)$$

where ε_{ij}^p —is the component of plastic strain, s_{ij} —is the component of stress deviator, whereas $d\lambda$ is a variable relating to the plastic strain.

Tensile rupture strength σ_r and yield stress σ_y characteristics of the ŽS6U alloy are presented in Fig. 4.2.

Due to the fact that maximum stresses occur for the maximum rotational speed, which is approx. 29,500–30,000 rot/min, static analysis was used in the simulation. The model also takes into account the contact in the fir tree slots, introducing a friction coefficient.

However, the most important stage is definition of boundary conditions. In Fig. 4.3a, pink colour denotes the surfaces that can only be displaced along the direction of the centrifugal force. Figure 4.3b presents another boundary condition—mounting of the disc section with blade in the rotation axis of the rotor. For the entire

Fig. 4.2 Characteristics of ŽS6U material

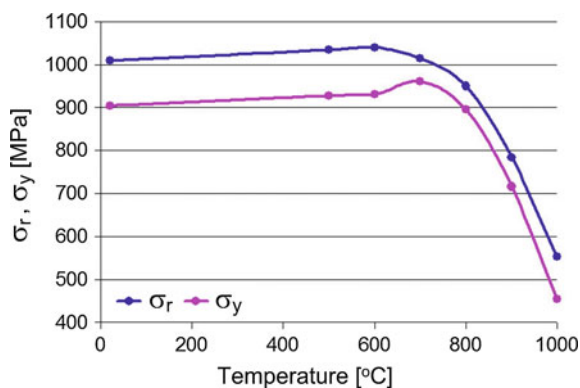
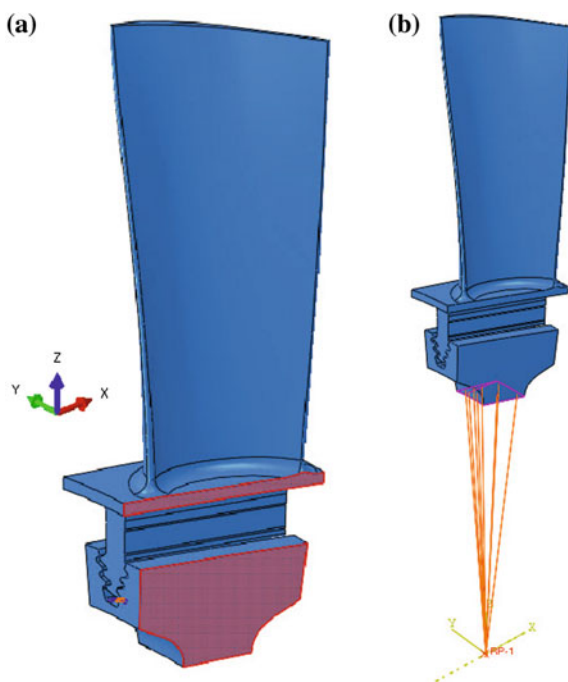


Fig. 4.3 Boundary conditions



model volume, rotational speed, which constitutes the main load, was also defined, equalling 30,000 rot/min.

The last step before running the analysis is applying the finite element mesh.

Due to the high degree of geometry complexity, C3D4 tetrahedron elements were used (Fig. 4.4). The effects of mesh density on results in the given blade point were also analysed. The amount of elements and differences in results between subsequent models are presented in Table 4.1.

Differences in results of 0.1–1 % prove that mesh density was selected properly.

Fig. 4.4 Element mesh



Table 4.1 Comparison of finite element meshes

	I mesh	II mesh	III mesh
	Amount of elements in models		
Mounting	14,682	17,624	30,252
Blade	51,540	82,892	184,961
Difference (%)	–	1.35	0.11

4.2 Analysis of Results

As a result of the conducted simulation, the Huber-von Mises reduced stress fields (σ_{red}) were obtained. Maximum stress values occur at its base on the negative pressure side, in close proximity to the edge of attack. In order to determine the values of loads more precisely and visualise their distribution within the blade, an A-A cross section was prepared. The maximum value noted was 454 MPa (Figs. 4.4, 4.5 and 4.6).

Fig. 4.5 Stresses in the blade

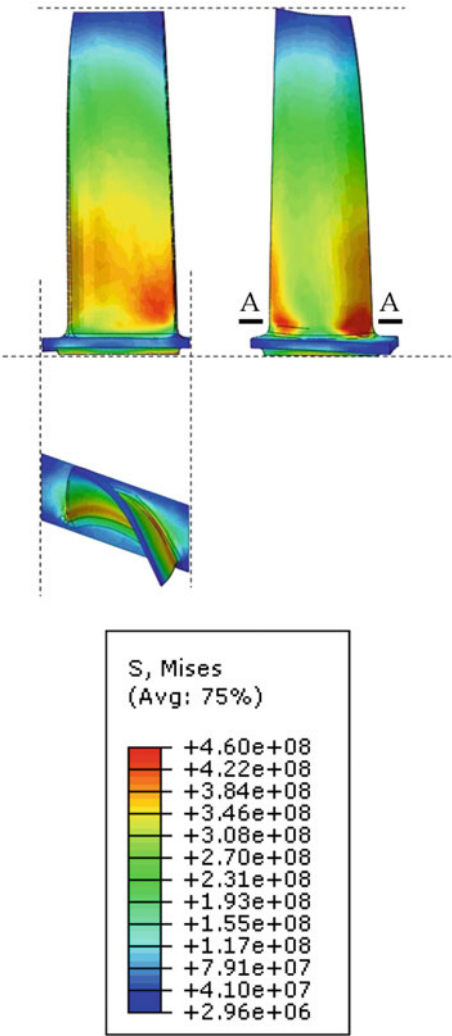
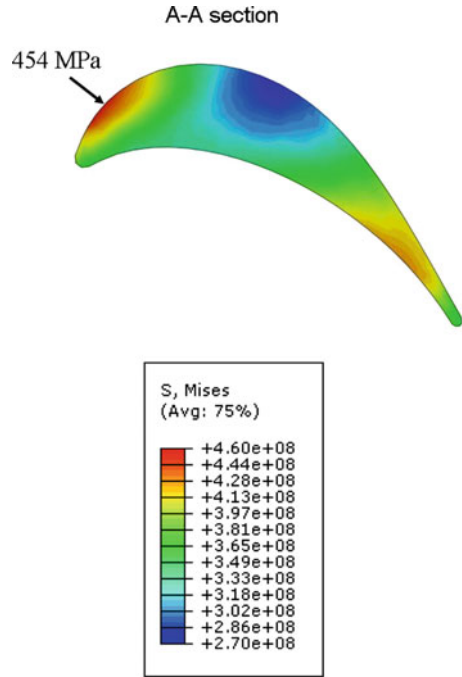


Fig. 4.6 Stresses in the dangerous cross section



The model presented in this point will be extended in the further chapter of the book for the purpose of analysing TBC damage in the most dangerous point of the blade.

4.3 Blade Vibrations Resonance

Main causes of turbine engine blade vibrations include the following:

- periodic changes of air and exhaust stream parameters in the engine's flow channel,
- impulse nature of the chamber combustion process,
- excessive engine imbalance,
- toothed wheels of reduction gears,
- effects of gravity forces.

Blade vibrations cause the occurrence of periodically changing fatigue stresses σ_f that can be (together with stresses resulting from other loads) the cause of serious engine damage. It is estimated that crossing this critical limit σ_f causes of up to 60 % of blade breaks, and breaking just one usually leads to damaging others and increasing engine imbalance, resulting in its unstable work.

In the case when frequency forcing the vibrations matches the blade's proper vibration frequency, resonance ensues, leading to increased deflections, which in turn result in increasing stress amplitudes. Longer operation under resonance may lead to blade damage or destruction as a result of material fatigue.

Knowledge of the blade's proper vibration forms and frequencies enables analysing the expected damage and effects of the scope and condition of the engines operation on occurrence of damage.

Assessing the blade's proper vibration frequencies is very difficult due to its complex shape and the nature of loads it is subject to. For this reason, the blade's vibration frequency and form are primarily determined by way of calculations using the FEM that make use of their three-dimensional numerical methods. Proper vibration frequencies and forms determined this way are subsequently verified experimentally at test sites.

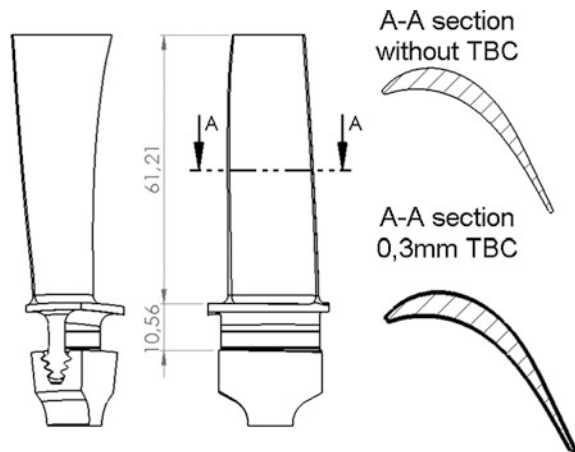
In order to determine the effects of ceramic TBCs on the vibration frequency, we have performed our own numerical tests. The object was a working blade of the engine. Two cases were considered, one where the blade had no coating, and the other with a TBC (Fig. 4.7).

The effects of rotor rotational speed and of temperature on the proper vibration frequency are presented in the later part of the subsection.

Figure 4.8 presents the first four forms of the engine working blade proper vibrations. With transverse vibrations (and only these), deflection occurs in relation to the axis of the profile's lowest stiffness, and cross sections perpendicular to the blade's longitudinal axis do not change their shape, and only deflect, remaining perpendicular to the bent axis (Fig. 4.8a). With torsional vibrations, transverse cross sections (profiles) of blades rotate around their stiffness centres without deformation (Fig. 4.8b).

Due to centres of mass and stiffness of a blade's transverse cross sections not matching, transverse vibrations cause the occurrence of torsional vibrations and vice versa, which lead to simultaneous transverse-torsional vibrations occurring

Fig. 4.7 Blade dimensions



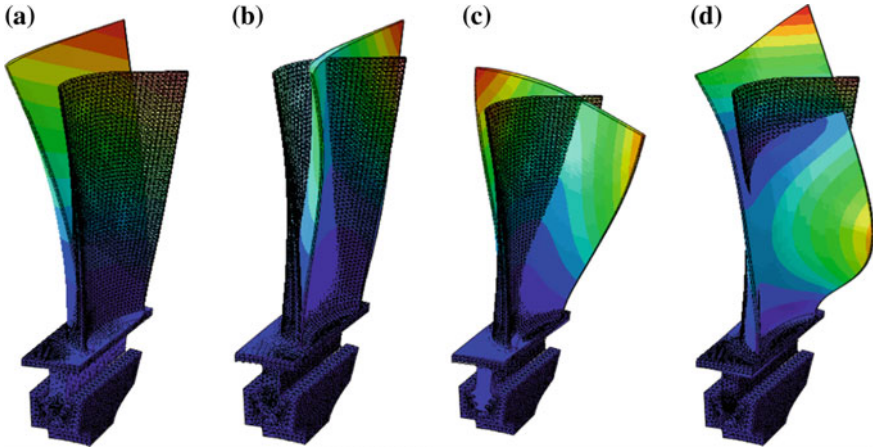


Fig. 4.8 Forms of PZL-10 W engine working blade vibrations: **a** transverse, **b** torsional, **c** transverse-torsional, **d** vibration node

(Fig. 4.8c). When local forms of blade vibrations occur, its transverse cross sections deform, and node lines also position themselves parallel to the blade's longitudinal axis (Fig. 4.8d).

In comparison to resting frequencies, rotor blade proper vibration frequencies change during an engine's rotational movement, since they are located in the centripetal acceleration field then. Centrifugal forces, affecting the blade body, have a stiffening effect on the blades, reducing vibration amplitudes and simultaneously increasing their frequencies with the increase in rotor rotational speed.

Figures 4.9, 4.10, 4.11 and 4.12 present numerical results of proper vibration frequency changes throughout the operating range for the considered engine blade, for a coatless blade and for one with a TBC ($t = 20\text{ }^{\circ}\text{C}$ for all cases). When analysing the charts, the effect of the rotational speed is the most visible for the first form, and vibration frequency increase is approx. 18 %, considering the extreme rotational speeds. The application of ceramic coatings results in decreasing the proper vibration frequency throughout the speed range, in the case of the coatless

Fig. 4.9 Results for the first proper vibration form

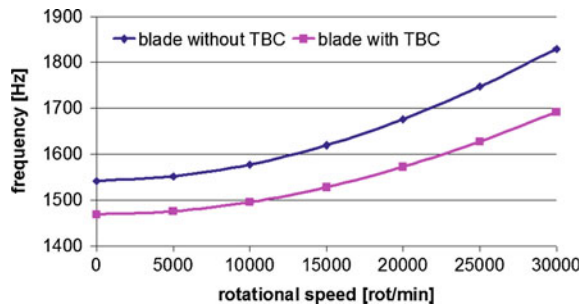


Fig. 4.10 Results for the second proper vibration form

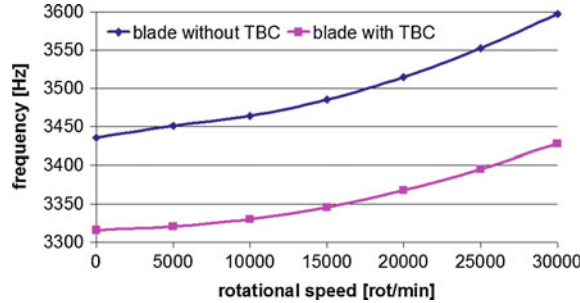


Fig. 4.11 Results for the third proper vibration form

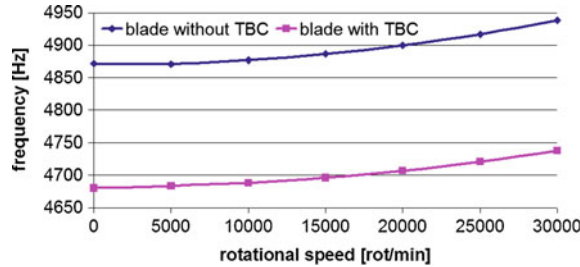
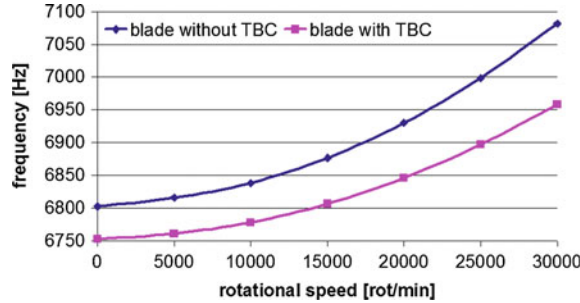


Fig. 4.12 Results for the fourth proper vibration form



blade. For the first form, these differences range from 4.7 to 7.4 % and increase with increasing rotational speed. For the fourth form, the differences are smaller and fall within the range from 0.7 to 1.7 % for the coatless blade.

Working part temperature significantly affects the blade’s proper vibration frequency. Temperature increase entails reduction of the material’s longitudinal elasticity modulus value, which causes a change in the proper vibration frequency [1].

Figures 4.13, 4.14, 4.15 and 4.16 present results of heating temperature of the PZL-10 W engine working blade profile section for a coatless blade and for one with a TBC (for rotational speed equal to 0). For all forms, a reduction in proper vibration frequency by approx. 12.8 % occurs in relation to an unheated blade.

Fig. 4.13 Results for the first proper vibration form

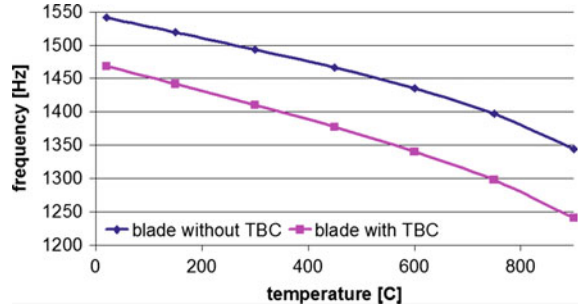


Fig. 4.14 Results for the second proper vibration form

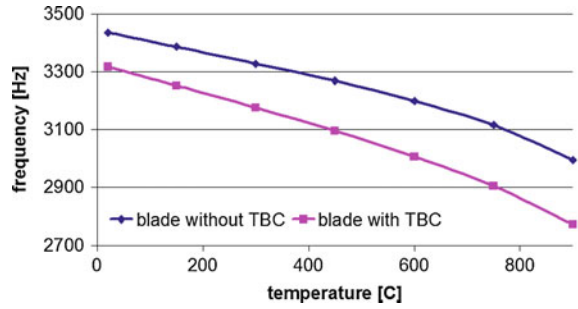


Fig. 4.15 Results for the third proper vibration form

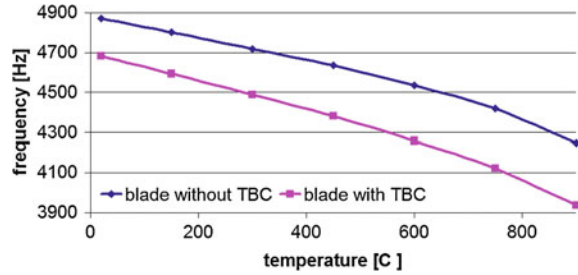
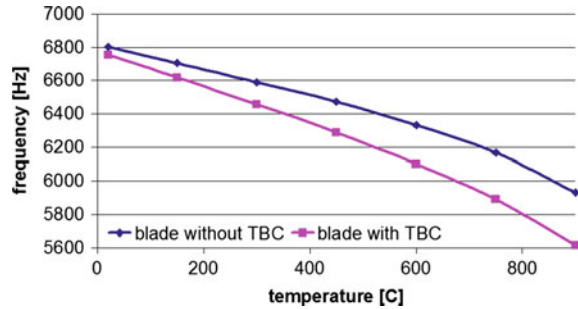


Fig. 4.16 Results for the fourth proper vibration form



The application of ceramic coatings results in decreasing the proper vibration frequency throughout the temperature range, in the case of a coatless blade. For the first form, these differences range from 4.7 to 7.7 % and decrease with decreasing temperature. For the fourth form, the differences are smaller and fall within the range from 0.7 to 5.3 % for the coatless blade.

The use of TBCs on the blade's working surface entails two changes affecting proper vibration frequency. It is a change of the cross section's moment of inertia, and change of temperature caused by the insulating properties of the ceramic coating.

4.4 Conclusions

When designing turbine engine blades, it is necessary to take into account the resonance phenomenon that may occur during operation. Due to the complex shape of the blade, as well as the effects of temperature and rotational speed on the blade's proper vibration, performing numerical tests is necessary. In the above section, the conducted numerical tests were discussed, determining the first four forms of proper vibrations, and analysing the effects of temperature and rotational speed on the frequency value.

Later in the book, the FEM model constructed in the ABAQUS program and the obtained results will serve as the global model during analysis of the most efforted micro- and macro-fragment, taking into account the TBC presence on the surface.

Reference

1. Balicki W, Chachurski R, Głowacki P, Godzimirski J, Kawalec K, Kozakiewicz A, Pągowski Z, Rowiński A, Szczeciński J, Szczeciński A (2010) Aviation turbine engines—construction—exploitation—diagnostics part 1. Scientific Library of the Aviation Institute, Warszawa (in polish)

Chapter 5

Environmental Loads

Turbine engines need to be supplied both with fuel and oxygen contained in the air. The most important parameter of aviation fuel is its chemical composition, which decides the fuel's operating properties [1].

In sandy areas, air composition may also change with the presence of hard particles which, moving in the turbine's flow through section at speeds of approx. 700 m/s, can lead to erosive destruction of turbine blades.

Therefore, a combination of several factors, such as presence of chemical compounds facilitating corrosion, hard particles and temperature, creates environmental loads that can lead to *corrosion*, *erosion* and—most commonly—both of these phenomena together.

Below, both of these factors will be discussed, mainly in relation to blades with TBCs.

5.1 Corrosion

Corrosion of combustion turbines is an adverse phenomenon limiting the ability to increase thermal efficiency due to the existence of critical temperature, above which rapid corrosion begins [2, 3]. Exhaust aggressiveness depends largely on the fuel's chemical composition and type, conditions of its combustion and temperature at which exhaust contacts the structural materials.

Corrosion occurring in protective coatings TBCs has been the object of several studies [4–9]. TBC layers were tested in turbines for the first time about 40 years ago. The Pratt and Whitney Company used zirconium-stabilised MgO, coating combustion chambers at the beginning of 1960s. Until the beginning of 1980s, YSZ coatings applied using the APS method were utilised. In the 1980s, a new technology of coating application was introduced—EB-PVD—and it was used for applying the top coat (TC) layer of rotating blades [8, 10].

The EB-PVD (Fig. 2.2) coating structure has a number of advantages. Due to the column-like structure, it is more flexible and better able to survive deformations occurring when the thermal expansion coefficients of the bond coat (BC) and top coat (TC) are not matched properly. Columns in an EB-PVD structure can move independently, which ensures high tolerance for deformations appearing during operation [1, 11]. Despite the advantages, the duration of operation can be significantly shortened, should CMAS corrosion occur. It is an abbreviation of the first letters of Latin element names such as calcium, magnesium, aluminium, and silicon [6]. Therefore, CMAS contains chemical compounds such as CaO , MgO , Al_2O_3 , and SiO_2 , which may be present in the air, particularly when taxiing on the airfield or during flight over desert terrain. It has been observed that very small particles, of a $10\text{ }\mu\text{m}$ diameter, can penetrate the purification system and reach the combustion chamber. Melting point of a mixture of such compounds ranges between 1240 and $1260\text{ }^\circ\text{C}$. These particles do not have sufficient kinetic energy to damage a TBC layer, but they are deposited on the edge of attack. A melted CMAS mixture penetrates into pores between columns, and degrades the coating chemically and microstructurally. As a result of cooling, CMAS changes its state and remains as a solid between EB-PVD coating columns. The coat's thermal and mechanical properties change this way. Its thermal conductivity increases, and the TBC no longer offers protection against thermal shocks and the coating loses its properties [4, 7]. Kramer [12] in particular studied the effects of CMAS deep within coatings and concluded that the mentioned melted mixture rapidly penetrates open structures of EB-PVD. Furthermore, Kramer calculated that CMAS needs less than one minute to penetrate $100\text{ }\mu\text{m}$ into a TBC, even at temperatures below $1240\text{ }^\circ\text{C}$. Maximum TBC operating temperature is therefore limited by CMAS capillary penetration into the coating structure.

According to the Honeywell Company, determination of a TBC layer lifespan depending on CMAS depends on the following factors that can be divided into groups:

- airplane operation: type of airfield, flight altitude, flight time, engine shutdown time;
- engine construction: inlet air filtration efficiency, TC temperature, BC temperature, TBC thickness, gas pressure, gas velocity;
- material: TBC microstructure, TBC composition.

In order to prevent CMAS from penetrating into spaces between columns, Honeywell employed YSZ spraying onto a layer of columns deposited by EB-PVD. On the other hand, Levi used $\text{Gd}_2\text{Zr}_2\text{O}_7$ sputtering on EB-PVD columns, which rapidly reacts with CMAS and creates a thick, $5\text{--}10\text{ }\mu\text{m}$ barrier that protects from penetration of the undesired mixture.

As reported in [5], one method of preventing corrosion can also be washing elements working at high temperatures in accordance to a specific procedure, depending on the airplane's role, e.g. before every take-off or once a month. An alternative method of determining the frequency of washing engine elements may be the use of a borescope.

In order to limit corrosion and CMAS occurrence, it is necessary to maintain air purity using high-efficiency filters and observing acceptable alkaline metal contents, e.g. for Na + K, the value for air must range between 0.2 and 0.6 ppm, 0.5 ppm for vanadium and a maximum of 1 % for sulphur. Another method of controlling corrosion can also be the use of fuel additives, e.g. an addition of magnesium can be used to control dangerous vanadium, as the resulting compound $\text{Mg}_3\text{V}_2\text{O}_8$ has a high melting point. Addition of tin is used for controlling NaCl by lowering its electrochemical potential [5].

As a last point, it must be noted that CMAS can be more dangerous for new engines, where higher temperatures and their gradients occur [6].

5.2 Erosion

During airplane taxiing on the airfield or during takeoff, solid particles present in the air may be drawn into the engine. Their majority is stopped at the compressor's blades, but the smaller ones can penetrate into the working turbine section [13]. Considering the aerodynamics, particles larger than 20 μm should not hit the edge of attack or its vicinity. Studies demonstrate that particles larger than 100 μm hit blades whose linear velocity is 500–600 μm and they have sufficient energy to erode TBC. A hit by a particle larger than 500 μm is sufficient to chip the TBC layer BC [6].

Erosion is commonly considered the second mechanism that thins TBC layers as insulation layers. In many cases, it is even removed completely [8, 14]. Furthermore, TBCs are more susceptible to erosion than fully ceramic materials, since they include porous structures. Coatings deposited using the APS method have 10–15 % porosity, while coatings deposited by the EB–PVD method have a column structure and porosity of approx. 10 % [10].

Comparisons of erosion speed of both these coat types were made in [10]. The eroding materials were aluminium or silicon particles having sizes 40–100 μm and speeds of up to 300 m/s. Various angles of eroding material impacts and various speeds, temperatures and particle sizes were analysed. The main conclusion was that in all cases, erosion speed for coatings deposited by the APS method was higher than for EB–PVD.

Depending on the utilised method of coating deposition (APS or EV–PVD), different stages or types of erosion can be distinguished. In paper [15], the authors identify three types for coatings deposited by APS:

- low erosion speed—low damage,
- medium erosion speed—damage around foreign particle impact site,
- high erosion speed—tunnel formations in the coating surface.

For EB–PVD coatings, at least two erosion mechanisms can be distinguished. They have been termed foreign object damage (FOD) and can be classified as follows:

- the FOD I mechanism applies to large damage transverse to the columns; this damage may propagate down to the thermally growth oxide (TGO) layer,
- the FOD II mechanism is a little different, as in this case, energy is absorbed during deformation (buckling) of the coating's columns.

Description of the foreign object impact itself on the EB–PVD structure is presented in [16] and comprises several stages:

- within 30 ns, an elastic wave propagates down to the TGO layer,
- tensile wave is reflected and propagated,
- at the same time, after 5–10 ns, the upper sections of columns are bent. The bending time is approximately 100 ns,
- after a longer time, approximately 50 ns, when the impact velocity and temperature are relatively high, plastic deformations appear,
- increased density zone develops for approximately 1 ms, until the foreign object is rebounded.

Detailed test results, effects of morphology and ageing on coating layers formed using the EB–PVD method are presented in [17]. These studies indicate that erosion rate decreases with decreasing column diameter, while ageing increases erosion rate. Foreign object impact angle on the sample surface was also taken into account. It appears that impacts perpendicular to the surface are not dangerous, while as the impact angle decreases, erosion rate rises, while the threshold value is an angle of 10° – 20° , when a catastrophic increase in erosion rate occurs. These studies stress how many factors affect the lifespan of protective coatings.

In [18], authors note that performing simulations of solid particle impacts on blades with deposited protective TBC layers is very difficult. It is caused for example by differences in the order of size of finite elements, assuming that column diameter is approximately 10 μm , the foreign object is 100 μm , while blade length is several tens of millimetres. This fact makes performing a reliable simulation with an accurately represented TBC layer impossible. However, as claimed by the authors, one of the main forms of deformation is bending of EB–PVD columns, and in this case 2D simulations should be employed.

As a result of difficulties in preventing micrometre-sized particles occurring in the exhaust gases, designers have limited trust for the utilised coatings, particularly on edges of attack [6].

5.3 Thermally Growth Oxide (TGO) Layer Growth

In a pure combustion gas environment, the coating lifetime is limited by TGO layer development, which causes damage process of the TBCs systems [6].

In order to increase the TBC lifespan, considering the damage mechanism resulting from TGO layer development, the following solutions are proposed [6]:

- reducing aluminium oxide growth,
- ensuring high TGO purity,
- minimising TGO-caused stresses,
- ensuring that α -aluminium is present in the TGO,
- slowing down BC rumpling,
- minimising mismatches in thermal expansion between the bond coat and the metal alloy,
- increasing BC resistance to creeping,
- improving adhesion between TGO and TC,
- improving adhesion between TGO and BC,
- minimising sulphur activity.

5.4 Author's Own Tests of Moving Blade Surface, Including Chemical Analysis

Figure 5.1 presents microscope-magnified images of two points on a turbine blade: at half of its length, and at its bottom part. Note that the blade has already reached appropriate service life and has been withdrawn from operation. Analysis of these points indicates that the blade's lower part is highly exposed to corrosion and corrosive affects of exhaust gases, demonstrated by visible pits that form the notches mentioned above.

Notches situated in the lower part of the blade are more dangerous, since that is where the maximum stresses originating from blade bending occur during its operation, as demonstrated by Fig. 5.2.

Fig. 5.1 Turbine blade surface

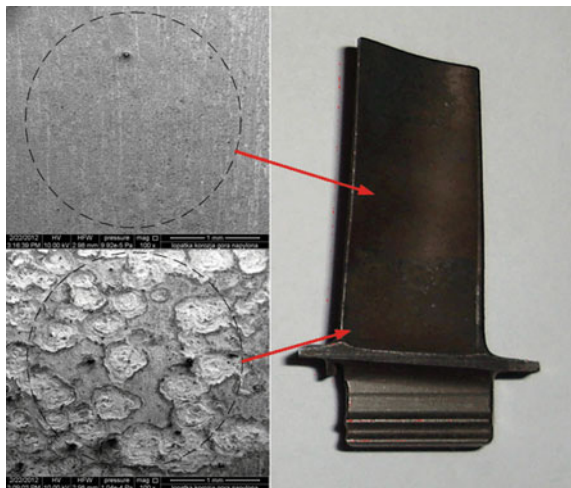
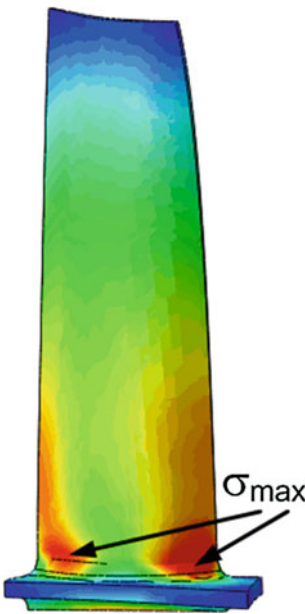
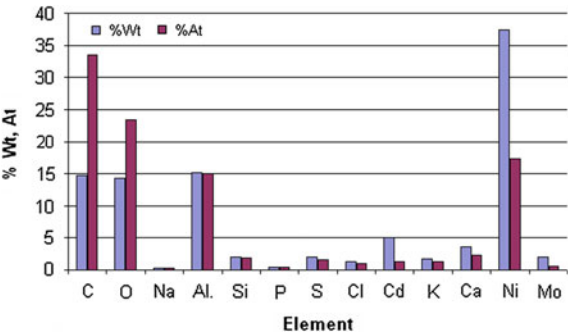


Fig. 5.2 Stress distribution in the turbine blade



Additionally, chemical analysis was performed for several points of the blade; in order to determine the percentage content of individual elements, their average content is presented in Fig. 5.3. In total 13 elements were detected, of which Ni, Al and Mo are elements comprising the alloy that the blade is made of, and their total share of weight is the greatest. The next element is carbon. It originates from aviation fuel combustion and takes the form of individual soot grains, as presented in Fig. 5.4. The next two elements with a significant percentage content are Al and O. Aluminium, as mentioned above, is also an element of the blade, and forms the Al_2O_3 compound with oxygen. Similar to Na, Si, K, and Ca, aluminium can also originate from the soil, e.g. during a helicopter’s takeoff or landing, dust rises and can be drawn into the engine. The presence of chlorine is also dangerous, as it can

Fig. 5.3 Chemical analysis of the surface



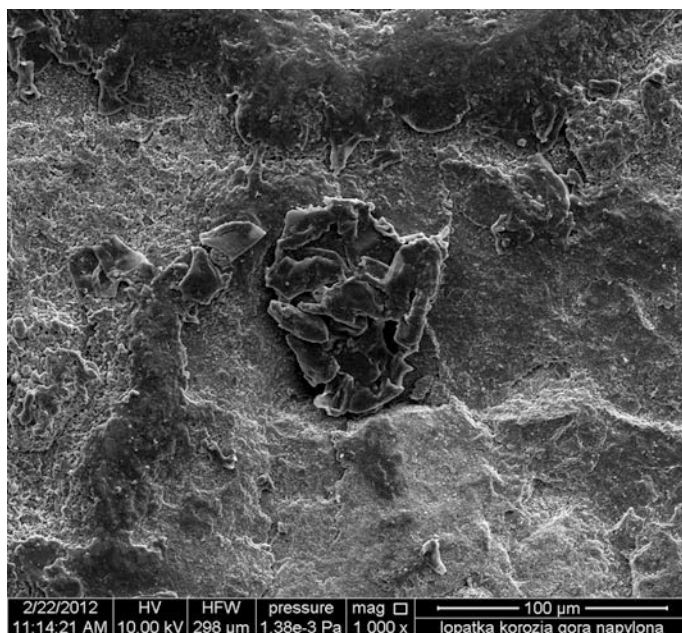


Fig. 5.4 Soot grain

form a compound with sodium, forming an aggressive environment that fosters corrosion.

Therefore, the relation of chemical and electrochemical corrosion with the forming pits caused for example by impacts of solid particles, like sand, will cause reduction in fatigue resistance of blades, as proven by results of microscopic observations and chemical analysis of the working surface.

5.5 Conclusions

Modelling corrosion and erosion environments is becoming a very difficult problem from the perspective of numerical simulations. The conducted microscopic observations of the blade after an exhausted service time indicate that there are places affected by corrosion to a greater and lesser degree. Modelling such phenomena would require performing FSI simulations, with moving solid particles that damage the blade additionally taken into account. At present, numerical methods are not so advanced in terms of chemical corrosion occurrence as well.

An interesting phenomenon is CMAS corrosion, which can be executed in micro-scale for EB-PVD coatings in order to assess how thermal and mechanical properties of the coating degrade, since columns filled with solidified CMAS are no longer flexible, so they can be damaged more easily.

References

1. Kortylewski W (2008) Combustion and fuels. Wrocław University of Technology Press (in Polish)
2. Mrowiec P, Werber T (1975) *Gas corrosion of metals*. Śląsk Press, Katowice (in Polish)
3. Tubielewicz K, Melechow R (ed) (2003) Materials used in heat power engineering. Works of surface treatment team, Częstochowa (in Polish)
4. Chen X (2006) Calcium-magnesium-alumina-silicate (CMAS) delamination mechanisms in EB-PVD thermal barrier coatings. *Surf Coat Technol* 200:3418–3427
5. Eliaz N, Shemesh G, Latanision RM (2002) Hot corrosion in gas turbine components. *Eng Fail Anal* 9:32–43
6. Strangman T, Raybould D, Jameel A, Baker W (2007) Damage mechanisms, life prediction, and development of EB-PVD thermal barrier coatings for turbine airfoils. *Surf Coat Technol* 202:658–664
7. Wellman R, Whitman G, Nicholls JR (2010) CMAS corrosion of EB PVD TBCs: identifying the minimum level to initiate damage. *Int J Refract Metals Hard Mater* 28:124–132
8. Wellman RG, Nicholas JR (2008) Erosion, corrosion and erosion–corrosion of EB PVD thermal barrier coatings. *Tribol Int* 41:657–662
9. Zschau HE, Dietrich M, Renusch D, Schutze M, Meijer J, Becker HW (2006) Detection of hydrogen in hidden and spalled layers of turbine blade coatings. *Nucl Instrum Methods Phys Res B* 249:381–383
10. Nicholls JR, Deakin MJ, Rickerby DP (1999) A comparison between the erosion behaviour of thermal spray and electron beam physical vapour deposition thermal barrier coatings. *Wear* 233–235:352–361
11. Johnson CA, Ruud JA, Bruce R, Wortman D (1998) Relationships between residual stress, microstructure and mechanical properties of electron beam–physical vapor deposition thermal barrier coatings. *Surf Coat Technol* 108–109:80–85
12. Kramer P, Yang J, Levi C (2006) Thermochemical interaction of thermal barrier coatings with CMAS deposits. *J Am Ceram Soc* 89:3167–3175
13. Chen X, Hutchinson JW (2002) Particle impact on metal substrates with application to foreign object damage to aircraft engines. *J Mech Phys Solids* 50:2669–2690
14. Steenbakker RJL, Wellman RG, Nicholas JR (2006) Erosion of gadolinia doped EB-PVD TBCs. *Surf Coat Technol* 201:2140–2146
15. Wellman RG, Deakin MJ, Nicholls JR (2005) The effect of TBC morphology and aging on the erosion rate of EB-PVD TBCs. *Tribol Int* 38:798–804
16. Chen X, He MY, Spitsberg I, Fleck NA, Hutchinson JW, Evans AG (2004) Mechanisms governing the high temperature erosion of thermal barrier coatings. *Wear* 256:735–746
17. Tassini N, Lambrinou K, Mircea I, Bartsch M, Patsias P, Van der Biest O (2007) Study of the amplitude-dependent mechanical behaviour of yttria-stabilised zirconia thermal barrier coatings. *J Eur Ceram Soc* 27:1487–1491
18. Crowell MW, Schaedler TA, Hazel BH, Konitzer DG, McMeeking RM, Evans AG (2012) Experiments and numerical simulations of single particle foreign object damage-like impacts of thermal barrier coatings. *Int J Impact Eng* 48:116–124

Chapter 6

State of Arts in Experimental Testing of TBCs Systems—Literature Analysis

6.1 Review and Analysis of Currently Utilised Tests

Tests of TBC strength properties are complex and require utilising many modern methods. This results in numerous scientific and technical problems arising during tests of strength properties of ceramic layers deposited by APS or EB-PVD methods. Their sources, related to:

- production technology of the TBCs,
- loading history of samples taken from different parts of the airplane engine,
- manner of laboratory samples preparation and type of utilised experiments.

The above problems can be grouped as follows:

I. *issues related to layer deposition:*

- selection of substrate material,
- selection of bond coat material,
- bond coat, top coat thickness,
- bond coat roughness,
- burner distance from the substrate, and its power (APS method),
- substrate heating before layer deposition (internal stresses).

II. *issues related to loading history of the samples: (1) taken from the real aero-engine, (2) new laboratory samples with artificial simulation of the real airplane loadings determined by:*

- Ageing—in order to trigger TGO growth,
- cyclical heating and cooling—in order to fatigue the coating material,
- number of cycles, time, temperatures, rate of heating and cooling, atmosphere.

III. *type of test employed to determine parameters of substrate cracking or critical deformation mechanics that lead to TBC damage:*

- uniaxial tensile test (UTT),
- bending test (3-PB, 4-PB, mixed mode, non-standard),
- barb test (pure shearing),
- indentation method,
- tearing test (double cantilever beam),
- elevated temperature tests,
- tests at various speeds,
- thermal fatigue tests.

IV. *types and methods of data acquisition during testing:*

- acoustic emissions,
- values of force, displacement and deformation,
- microscopic tests.

Solving these problems were published in many articles concerning the experimental testing. Below, a summary analysis was performed for each of the above points in turn.

I. *issues related to TBC layer deposition.*

The most obvious solution that comes to mind when selecting the substrate material for experimental testing of the TBCs systems is a material identical to that which the blade itself is made of. These are nickel-based superalloys, such as Inconel 718 [1, 2], Inconel 738LC [3, 4], Inconel 625 [5], CMSX4 [6–8].

The listed alloys are characterised by excellent strength properties, and consequently they are very difficult to work, less available on the market and relatively expensive. For this reason, several papers [9–12] mention the material SUS304, according to a Japanese standard, and it is a polish equivalent of stainless, chrome–nickel steel 0H18N9, widely available on the market, e.g., as rolled sheets.

There is also a range of samples similar to those used in tearing tests [13], where making the whole sample of Inconel or 0H18N9 steel would be rather expensive, and due to its strength, difficult. Therefore, in low-carbon steel is used in such cases. This is particularly important when not conducting ageing tests at high temperatures. Low-carbon steel has also been used as substrate in studies [12, 14]. Thermal and mechanical properties of low-carbon steel are commonly available in literature, e.g. [15].

The closest to reality is using substrate cut out directly from a blade (from a relatively flat part), e.g. [16]. These samples had dimensions $0.5 \times 2 \times 12$ mm, which requires specialist universal testing machines, as loading forces during bending are in the order of several tens of millinewtons.

Another issue is *surface preparation and related roughness*. The primary criterion that a TBC system must meet is providing very good adhesion between BC and the ceramic TC [6, 8, 10, 17]. In a large majority of studies, this parameter was ignored, although several authors did study its effects on TBC systems. In paper [8], authors analysed samples subjected to bending, where roughness was $R_a = 8.71 \mu\text{m}$ and $R_a = 9.52 \mu\text{m}$. It was achieved by using powders with different granularity.

Crack propagation was studied and energy release G_c (Nm) was compared. For samples subjected to various ageing times, from 0 to 200 h, it could not be concluded that ageing had any effects. The differences are in the order of a few percent.

Authors of paper [6] voice another opinion, as the results of their tests demonstrate that roughness $R_a = 10 \mu\text{m}$ results in extending a TBC system's lifespan in comparison to samples with roughness $R_a = 7 \mu\text{m}$. Therefore, as can be seen, there are some differences on this subject and comprehensive studies are required.

The next issue concerns *bond coat thickness and material*. The BC constitutes an intermediate phase between the substrate and the ceramic coating. It fulfils several important roles. First of all, it serves:

- to compensate deformations resulting from differences in thermal expansion of the substrate and the coating,
- as a source of Al, since a sealing layer of Al_2O_3 forms during operation,
- to provide coating adhesion to the substrate.

In general, the material that the bond coat is made of is described using a MCrAlY formula, where M is Ni and Co. The bond coat percentage composition varies, for, e.g. comprising 32 % Ni and 21 % Cr or 23 % Ni and 8.5 Cr. This issue also requires a more precise expression of information, tabulation guaranteeing that specific substrates and TC are used with appropriate BC that provide optimum cooperation in all ranges of temperatures.

Instead of selecting an appropriate chemical composition, authors of study [12] consider using FGM (Functionally Graded Material) layers. Here, a system composed of 6 layers was used: 100 % YSZ, 80 % YSZ + 20 % BC, 60 % YSZ + 40 % BC, 40 % YSZ + 60 % BC, 20 % YSZ + 80 % BC, 100 % BC. Such structure results in increased resistance to thermal shocks.

In order to confirm the phenomenon of quick degradation of a standard coating, authors of this study have performed their own tests using the ABAQUS program, involving the application of a compressed thermal-displacement step for a section of a standard coating (substrate, BC, TC) and for an FGM coating described above. Dimensions of both coatings are provided in Fig. 5.3. The simulation concerned a steady state, where a temperature of 1000 °C was maintained in the upper part of the coating, while 20 °C—in the lower.

Material data is summarised in Table 6.1. In the case of the FGM coating, this rapid increase occurs only for the last coating, counting from the substrate, while for the other layers, no large temperature jumps are visible. Of course, temperature jumps are undesired, since when the contacting phases differ in thermal expansion, thermal stresses appear.

As a result of the conducted simulation, temperature fields were obtained, as in Fig. 6.1. In standard coatings, a “cold” zone can clearly be distinguished of the substrate and BC, and subsequently a quite quick rise up to the maximum temperature after passing the boundary between BC and TC.

Ultimately, what the effect of non-uniform temperature fields and their rapid jumps is can be observed in Fig. 6.2. Normal stresses on a direction along the x axis

Table 6.1 Material data of an FGM coating

	Temp. (°C)	Substrate	Bond coat (BC)	Top coat (YSZ)	80 % BC + 20 % YSZ	60 % BC + 40 % YSZ	40 % BC + 60 % YSZ	20 % BC + 80 % YSZ
Young's modulus (GPa)	25	200	200	85	177	154	131	108
	1000	150	120	35	103	86	69	52
Poisson's ratio	25	0.33	0.3	0.1	0.26	0.22	0.18	0.14
	1000	0.33	0.3	0.1	0.26	0.22	0.18	0.14
Thermal ex. coeff. (10 ⁻⁶ 1/K)	100	10.8	10	5.2	9.84	9.68	9.52	9.36
	1000	16.8	17.5	10.5	16.1	14.7	13.3	11.9
Density (kg/m ³)	25	8500	7380	3610	6626	5872	5118	4364
	1000	8500	7030	3510	6326	5622	4918	4214
Specific heat (J/kg K)	25	440	450	505	461	472	483	494
	1000	700	980	630	910	840	770	700
Thermal conduct. (W/mK)	25	8.9	10.8	0.9	8.82	6.84	4.86	2.88
	1000	21.6	32.1	0.3	25.74	19.38	13.02	6.66

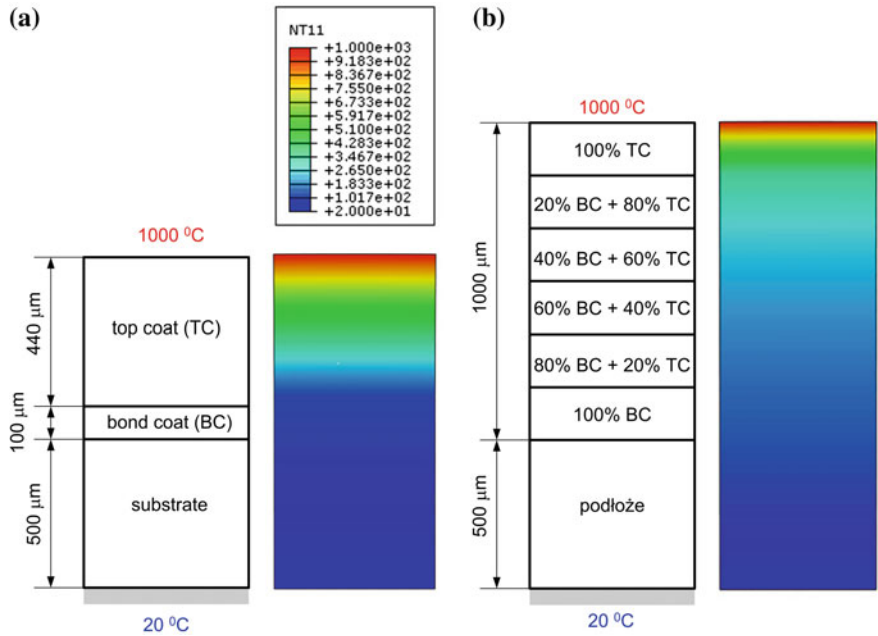


Fig. 6.1 Temperature distribution for: **a** standard and **b** FGM coatings

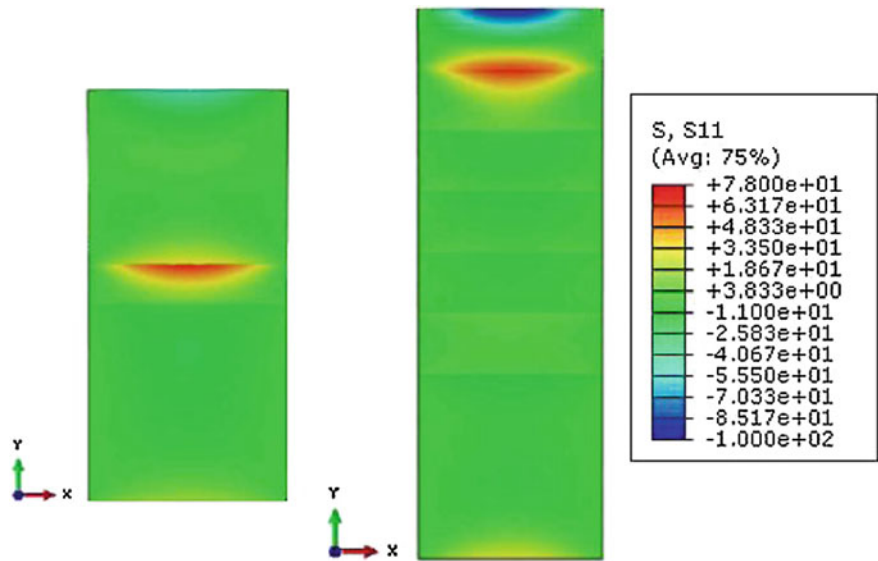


Fig. 6.2 Distributions of normal stresses σ_{11} for a standard coating and an FGM coating

are displayed here. For a standard coating, the stress jump is visible on the boundary of the BC and TC layers, while for the FGM system—on the boundary of the 100 % YSZ and 80 % YSZ—20 % BC layers. These are tensile stresses and if the threshold is exceeded, then the standard layer will be degraded very quickly. It must also be stressed here how important contact and adhesion at the interface of BC and TC are for standard coatings.

Similarly, in actual tests, the authors also observed a higher durability values for FGM-based coatings. However, a coating of this type has at least two basic drawbacks:

- relatively high thickness (1 mm) of the coating is in many cases unacceptable, as it significantly affects flow parameters in the turbine. Generally speaking, the coating simply becomes “too thick”,
- much higher costs related to longer and more complicated spraying process.

These two factors led to a current lack of information on practical applications of such solutions in literature.

An important technological parameter during BC and TC deposition is the *burner's distance from the coated surface, as well as its power*. The effects of a plasma burner's distance and power on strength parameters are discussed in studies [10, 12, 13, 18].

Paper [18] analysed the effect of burner's power for a $\text{Al}_2\text{O}_3/\text{ZrSiO}_4$ coating with a 3:2 ratio. Two powder types were utilised: regular dried, and one undergoing spheroidisation in the plasma stream. The powder that undergoes spheroidisation not only has a regular shape, but is also devoid of visible pores at the same microscope magnification. Therefore, the TC layer structure is more cohesive and offers better sealing, which leads to greater durability and delays TGO layer growth. Consequently, the use of dried or spheroidising powders is another technological parameter that may affect the coating's strength parameters and durability.

In study [18], the authors tested five sample types in total. Two types of 40 kW-power devices and a computerised 100 kW system were used to create the ceramic layers. Samples were designated as follows: SD40, SP40, SD100, SP100A, SP100B, where individual letters mean: D—dried powder, P—powder subjected to spheroidisation, A—plasma arc energy 15 kW, B—plasma arc energy 19 kW. Numbers mean the power of the device. The obtained results lead to concise, clear conclusions:

- the use of the spheroidised powder-based coating, at the same burner power, leads to increasing cracking resistance in approx 60 % SD40 and SP40 samples,
- use of greater burner power, with the same powder, leads to increased cracking resistance in approx. 86 % of SD40 and SD100 samples.

The effects of plasma burner distance on mechanical properties was also analysed in paper [13]. The Al_2O_3 layer was executed using GP-80, JIUJIANG system, 80 kW class. The authors describe the type of utilised gases, their pressure and flow values in detail. Coatings were deposited using a 39 kW arc at four different distances from the substrate: 70, 90, 110 and 130 mm. For each of the listed

distances, six TDCB (Tapered Double Cantilever Beam) samples were prepared. After conducting observations of the damaged surface, it was noted that cracks developed at interface between the metal sample and the coating. Preparing the six samples was important in this case, as the authors provide information on the spread of results as well. It is the lowest for 70 mm distance of burner from the substrate, and the highest for 90 mm. A sudden drop in energy release rate is also clearly visible after exceeding 110 mm. Therefore, the most beneficial is positioning the burner 70 mm from the substrate surface.

Exactly the same distance was utilised by the authors of study [10], achieving energy release rates ranging from 22.15 to 37.8 J/m².

Similarly, in paper [12] a negative effect of increasing the plasma burner's distance at ranges above 110 mm can be observed. In this study, not only burner distance but also substrate thickness were taken into account. In total, six types of samples can be distinguished, which were deposited from a distance of 120 mm at 32.5 kW power, and from distances of 125–130 mm at 38.5 kW power. Three substrate thicknesses were utilised: 1.5, 3 and 5 mm. The authors gathered the results in a chart of density of cracks per 1 mm in a function of deformations. They formulated the following conclusions:

- cracks appear earlier for samples which had their layer sprayed from a distance of 125–130 mm,
- crack density, for the given deformation, is greater by 30–50 % for coatings deposited from a distance of 125–130 mm.

At the end of this subpoint, study [1] must be noted. It raises the extremely important subject of obtaining information on material parameters for actual coatings by directly testing them. The paper concerns EB-PVD coatings that have a column structure, usually of a 0.2–0.3 mm thickness. Direct testing of materials with such low thickness is very difficult in practice. The authors proposed a method that involved creating an EB-PVD layer on a substrate without a BC, while the TC itself was deposited in multiple stages, and its thickness reached 1 mm. BC was omitted in order to make distinguishing the TC easier.

Another important issue when depositing TBC layers is occurrence of *internal stresses* [19, 20]. This issue mainly applies to the APS method, since the EB-PVD process is performed in a completely different manner. In order to improve the properties of the deposited coatings, it is necessary to identify every process, so that information on internal stress values and changes can be obtained.

For the needs of this monograph we performed own numerical simulations in ABAQUS system aimed at determining how stress values change, both in the blade and in the coating itself, for cases with blades heated to various degrees and with various thickness of single-stage sprayed layers. Two coating deposition temperatures were considered in the study: when the blade was at an ambient temperature, which was assumed to be 20 °C, and when the blade was pre-heated to 500 °C, i.e. the temperature of molten top coat.

The total layer thickness was 0.4 mm. Three cases were considered, where a single layer had a thickness of:

- 0.04 mm—10 layers in total,
- 0.08 mm—five layers in total,
- 0.2 mm—two layers.

Therefore, the simulations required constructing ten, five and two models, depending on the layer thickness. Figure 6.3 presents mesh views for all ten models.

For example, for the model with 10 layers, 85,395 CPS4T and 238 CPS3T elements were used in total, out of which, 1879 CPS4T and 34 CPS3T elements for the blade.

Time intervals between depositions of individual layers were 10 s. It must be stressed that each subsequent model, starting from the second, drew information on the distribution of temperatures and stresses from the previous model. Therefore, its “thermal history” was taken into account. In effect, after an entire cycle of depositing a 0.4 mm-thick layer, the maximum stresses in a blade, for a blade without pre-heating, were 818.8 MPa (Fig. 6.4), while for a pre-heated blade, up to 500 °C—84.25 MPa (Fig. 6.5). It is therefore almost a tenfold drop in stresses.

More detailed results are presented in the charts (Figs. 6.6, 6.7 and 6.8). They summarise the changes in Huber–von Mises reduced stresses, both for the blades that had an ambient temperature of 20 °C, and for blades pre-heated to 500 °C before layer deposition. The 10-s time intervals, corresponding to TBC layer deposition stages, are marked on the horizontal axis.

Analysis of the above charts leads to the following conclusions and observations:

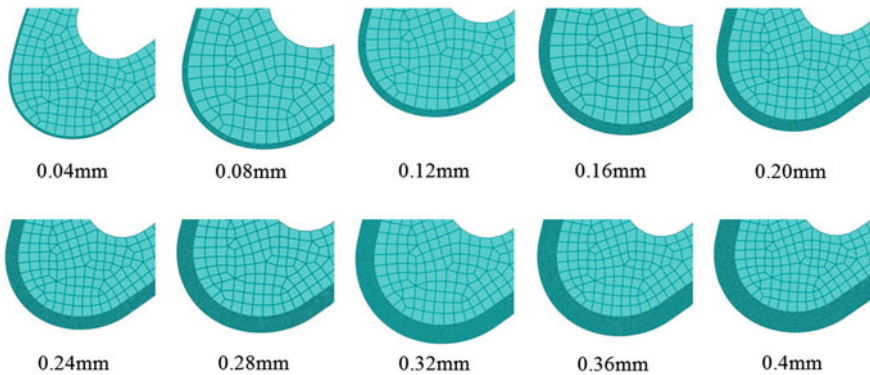


Fig. 6.3 Stages of TBC layer deposition

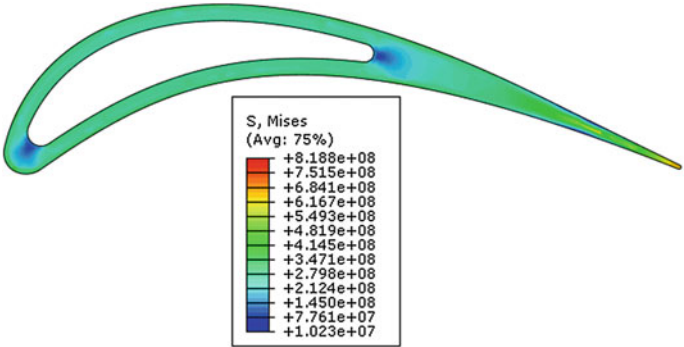


Fig. 6.4 Huber–von Mises reduced stress distribution for a non-heated blade (max—818 MPa)

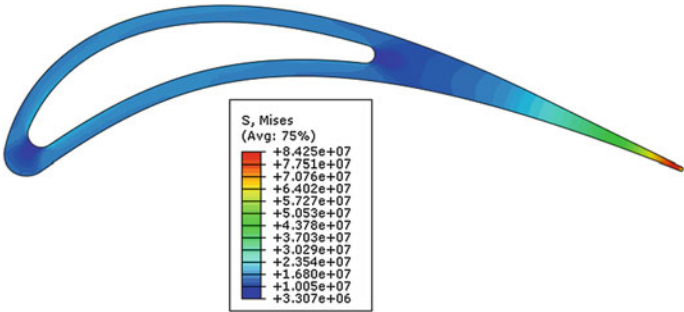


Fig. 6.5 Huber–von Mises reduced stress distribution for a heated blade (max 84.25 MPa)

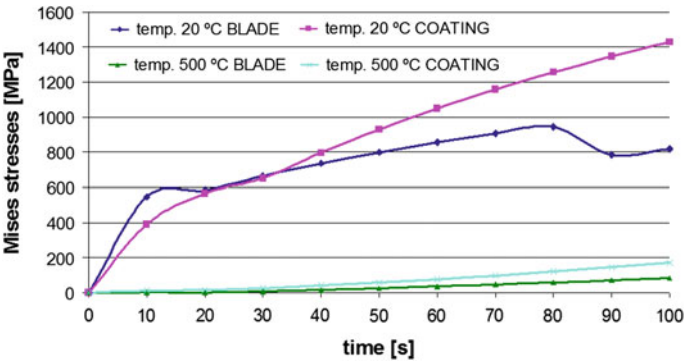


Fig. 6.6 Change in maximum Huber–von Mises reduced stress values for single 0.04 mm layers

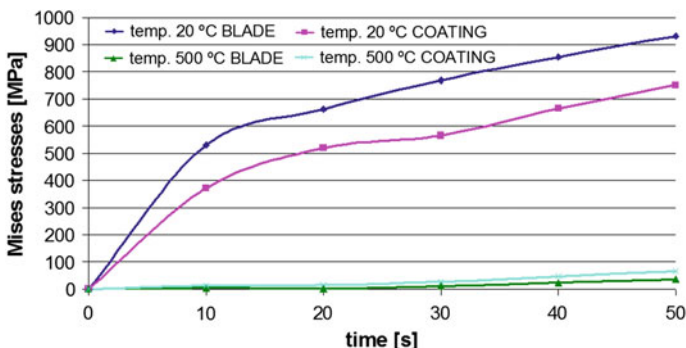


Fig. 6.7 Change in maximum Huber–von Mises reduced stress values for single 0.08 mm layers

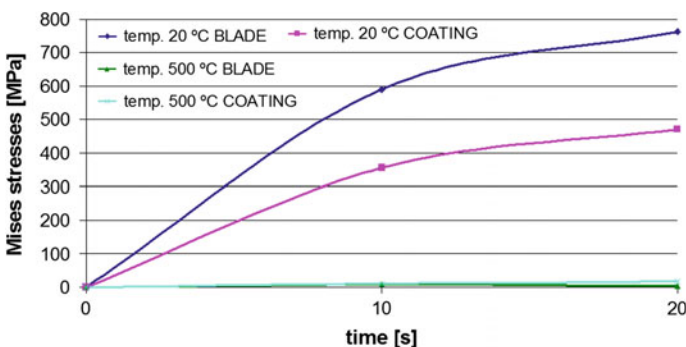


Fig. 6.8 Change in maximum Huber–von Mises reduced stress values for single 0.2 mm layers

- stresses in the coating are from 7 to 27 times higher for cases when the blade is not heated. Pre-heating should therefore be applied, as the ceramic layer may be damaged during deposition.
- stresses in the blade itself are lower for pre-heated cases as well, and their values range from 10 to 900 MPa,
- it is more beneficial to deposit layers with a greater thickness, which consequently enables reducing the maximum value of stresses that occur in the deposition process by approx. 50 %.

II. *issues related to loading history of the samples: (1) taken from the real aero-engine, (2) new laboratory samples with artificial simulation of the real airplane loadings.*

In laboratory tests, the important is knowledge of loading history of samples selected from the real structure of jet engines which results from exploitation conditions. In case of new samples with deposited TBC on the substrate it is

necessary to perform preparatory works before performing strength tests. The samples are subjected to an ageing process that simulates actual thermal loads in an engine. The ageing process was analysed in the following studies [1, 2, 6–8, 10, 21, 22]. On the other hand, the ageing was ignored in papers [3–5, 11–13, 23].

The papers that took the ageing process into account are characterised by a common values of the temperature level usually equalling 1000 °C, and the number of ageing hours counted in the hundreds. Despite the significant efforts by the authors, in many works some important phenomena are still ignored, such as:

- mechanical loads of the substrate, imitating stretching and bending that an actual blade is subjected to, are not taken into account,
- ageing, in most cases, is performed in laboratory furnaces, where the atmosphere is completely different from an actual engine,
- cyclical thermal shocks are not taken into account. Heating and cooling takes a relatively long time—from ten to several tens of minutes.

It would be difficult to cite the results of all works. For this reasons, only four most original and comprehensive studies that provide practical information will be presented.

Tests on a rather large number of samples with standard TBCs were conducted in [10]. The thermal ageing cycle consisted of a 10-min heating from room temperature to 1000 °C, annealing in this temperature for 100 min, and subsequently 10-min cooling. These cycles were conducted for 48 and 100 h. Also samples not subjected to ageing were tested. Additionally, the authors analysed the effects of thickness of TC deposited by the APS method for 200, 300 i 400 µm. The BC thickness remained constant and equalled 100 µm. For each configuration (TC—ageing cycle), five dumbbell samples were prepared for UTT that were performed at 1000 °C as well. During the test, transverse cracks on the coating's surface could be observed. The authors propose that the cracking process be divided into three phases:

- initial cracking—substrate deformations to trigger this phase can be considered critical, and this is a valuable information for designers,
- appearance of multiple cracks—in this phase, the blade's coating no longer fulfils its protective role,
- saturation with cracks—only the substrate itself is deformed, with no new cracks in the coating appearing.

In the study, despite using a large number of samples for testing and several different coating thicknesses, it is difficult to formulate clear conclusions. They can be grouped as follows:

- increased coating thickness does not increase its durability in any way. The best results are achieved for 200 µm—thick coatings. However, this assessment must be made carefully, as samples of this type with various thicknesses are actually not subjected to the same load conditions, since when thickness

increases, the bending moment acting on the layer also increases, and consequently loads increase as well.

- contrary to the what may appear, subjecting samples to ageing even for 100 h at 1000 °C does not cause degradation of durability, but its improvement, and, e.g. for samples with 200 μm coating, the following critical deformations occur: without ageing—3.25 %, 48 h ageing—3.6 %, 100 h ageing—4 %. This increase in critical deformations may be caused by the phenomenon of sintering of the coating's porous structure.

In that paper, no information is given on measurements of the sample's deformations. There is also no information on whether an extensometer was used for high temperatures. It can be guessed that deformations were calculated knowing the sample's elongation and its initial dimensions, but this method lacks precision.

For the purpose of this monograph, we conducted our own numerical simulations for the examples considered in paper [10] to demonstrate the effects of the coating's thickness. Material data was drawn from Table 6.1 for the temperature of 1000 °C. Figure 6.9 displays a scaled image of deformations of a sample whose one end was fixed, while the other was displaced by 0.08 mm, so that the sample worked in an elastic manner. The middle section, for which deformation and stress values were read at a later stage, is marked in red.

Figure 6.10 displays the deformation fields ε_{11} and stresses σ_{11} at the x_1 direction. Readings for extreme values occurring in the top and bottom parts of samples were also taken (Table 6.2). It is easy to observe—deformations in the sample's cross-section are non-homogeneous and between the top and bottom surface with the TBC coating, differ by approximately 28–48 %.

III. *type of test employed to determine parameters of substrate cracking or critical deformation mechanics that lead to TBC damage.*

Experimental tests that are presented in literature available to date can be divided depending on:

1. method of loading:

- uniaxial stretching (UTT),
- bending,
- shearing,
- bending with shearing,
- bending with stretching,
- bending with compressing,
- complex, unknown state of stress with the use of indenter imprint near the tested layer.



Fig. 6.9 Deformation of a sample stretched in axis x_1

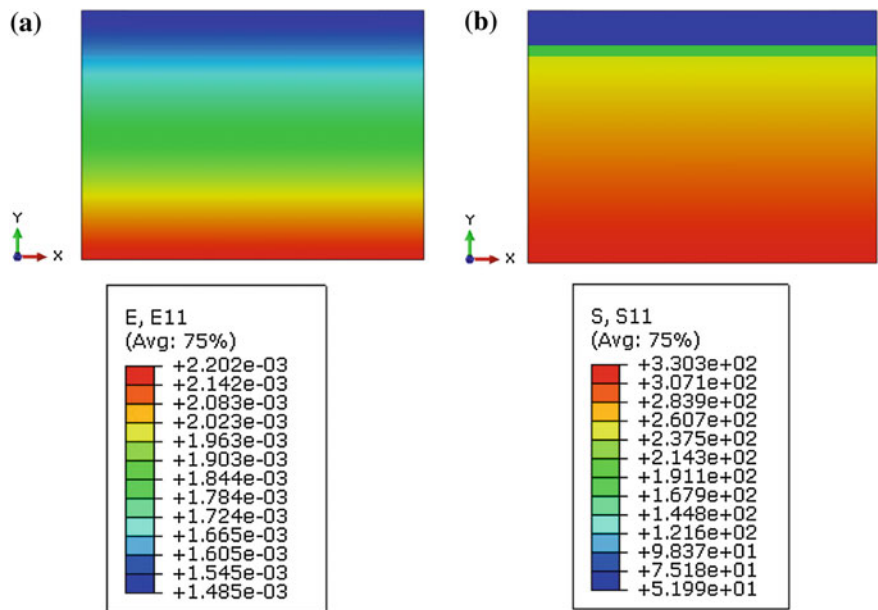


Fig. 6.10 Deformations characteristics: **a** deformation fields ε_{11} , **b** stress fields σ_{11}

Table 6.2 Comparison of results for top and bottom sample surface, and for different thicknesses of TBCs

	σ_{11} (MPa)		ε_{11} (%)	
	Top surface	Bottom surface	Top surface	Bottom surface
No coating	300.4		0.2	
0.2 mm coat	58.38	321.5	0.167	0.214
0.3 mm coat	55.31	325.8	0.158	0.217
0.4 mm coat	51.99	330.3	0.148	0.22

During blade operation, the greatest stresses originate from stretching and bending, so these two tests are the most important from the perspective of TBC tests.

2. temperature, at which the test is performed:

- tests at room temperature,
- tests at elevated temperatures.

Only tests that take temperature effects into account should be performed, as it is consistent with actual operating conditions of engine turbine blades.

3. structure of the tested sample:

- substrate + bond coat + top coat,
- substrate + bond coat + top coat + additional element,
- top coat.

The most important problem influencing the quality of experimental results is a large degree on the precision of samples manufacturing and the manner of their loading. An example can be the TBC layer wall test presented in [4, 24].

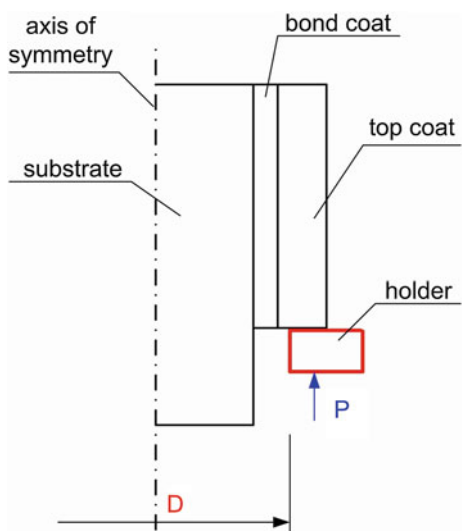
As an illustration we performed their own numerical tests concerning the effects of holder shape used in the TBC layer shearing test shown in Fig. 6.11. They took into account the varied diameters D of the tool shearing the TBC layer.

Figure 6.12 presents how the force value changed during the shearing test, up to delamination from the substrate or BC, for different positions of shearing tool contact.

Considering the extreme values, the difference is approximately 50 %. To put it more graphically, if a 0.7 mm-wide machining tool, i.e. “too wide”, is made, then the resulting error will be exactly on this level. Additionally, there is the matter of the machining part’s flatness deviation, and if the layer’s surface does not adhere closely to the tool, the results will be even more different.

Figure 6.13 presents the simulation results as Huber–von Mises stress fields for all analysed cases and for the same displacement of TBC layer, equalling $u = 2$ mm. Additionally, for the purpose of better visualisation, the scale has been streamlined, and the maximum values of Huber–von Mises reduced stresses have been provided under individual images. Analysis of the photographs indicates that the smallest concentrations occur when the greatest surface is in contact. However, even in this case pure shearing does not occur.

Fig. 6.11 Scheme of the TBC layer shearing test



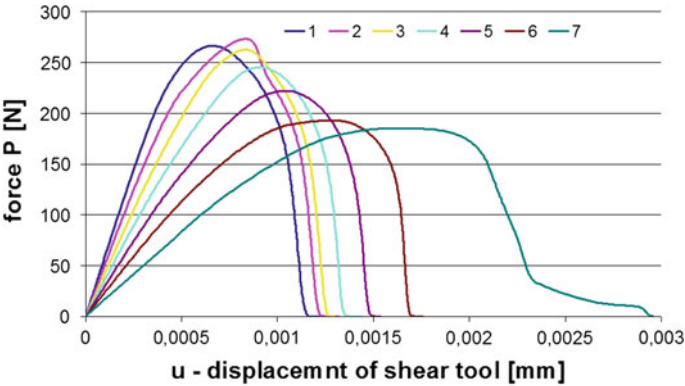


Fig. 6.12 Forces destroying the TBC layer during the shearing test

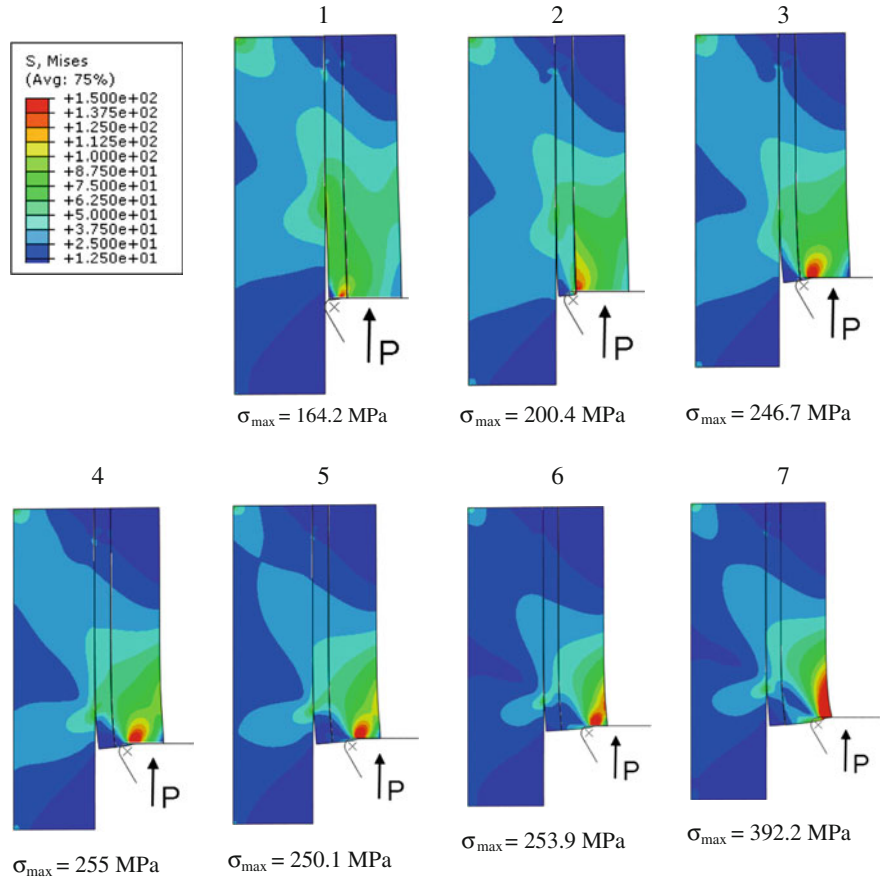


Fig. 6.13 Huber–von Mises stress distribution for the studied cases

Some of the works present samples technically very difficult to produce [1, 3, 25], which makes conducting tests more difficult. The very fact that substrate and coating layer thicknesses are in the order of tenths of a millimetre creates a certain challenge.

Paper [3] presents an interesting method of loading samples in a complex state (compression + bending). However, a significant obstacle is making a cut that is merely 0.1 mm-wide, separating the substrate from the TBC system. This cut, as stated by the authors, was made with a diamond disc.

Another difficult, and as stated by the authors in paper [1], time-consuming example is the manufacturing of an EB-PVD sample, depositing it several times on the bond coat-less substrate, so that only the layer itself can be removed later. Ultimately, the sample made using the EB-PVD method was 1 mm-thick and was subjected to a 4-point bending test.

A third example will be the sample demonstrated in study [7]. Small specimens were similar in shape to the double cantilever beam geometry. By making the cut and applying the eccentric force, a complex stress state was achieved, very close to that experienced by a blade in the most stressed point at its base, i.e. bending with compression. The sample was 3.5×4.9 mm in size and was small enough for the test to be carried out under a microscope. This therefore required, similarly to paper [1], the use of an original holder.

In study [26], the authors noted the phenomenon of coat creeping under longer-lasting loads, also introducing so-called thickness coefficient, which is the thickness ratio of surface substrate to coating TBC. Numerous simulations demonstrating how normal, tangent and reduced Huber–von Mises stresses change for different thickness coefficients and load durations.

The method of heating samples is also a matter of debate. It can be done in two ways by placing the sample in:

- a chamber with halogen lamps or other electric-powered heat sources (as in paper [6]),
- an acetylene-oxygen torch can be used [27].

Each of these methods has its drawbacks and advantages, although—considering that the TGO layer grows slowly and the acetylene torch exhaust or heated air atmosphere has no effect on its growth rate—the best solution becomes using an electrically powered chamber.

IV. types and methods of data acquisition during testing.

Not only sample manufacturing quality, but also the manner in which information on the TBC system's condition under load is collected will be important for obtaining correct data from the experiment. The main test methods of data acquisition, based on conducted tests, are presented below:

- *acoustic emissions (AE)*

The TBC system is a highly specific composite material and its most important part, responsible for durability—the interface of coating with substrate—is invisible during the test itself. This contact is largely uneven, which was the subject of numerous articles, and furthermore, it changes during blade operation at high temperatures, when TGO layer grows. On account of such complex structure and occurring changes, one method of observing the phenomena during strength tests is to make use of acoustic emissions. For example, AE were used in papers [6, 22, 28, 29].

In study [6], two sensors with a range from 300 to 800 MHz were employed. In publication [22], it was a sensor adapted to high temperatures, with a frequency of 70 kHz. The authors used noise cut-off at 45 dB. On the other hand, one sensor was used during a 4-point bending test in paper [28] in order to determine the critical deformations for samples subjected to different numbers of thermal cycles. In [29], the recording frequency was 1 MHz, while noise was cut-off at a lower level than in paper [22], namely 38 dB. During UTT tests, two sensors positioned on the substrate side were used.

- *values of force, displacement, deformation.*

During strength tests, it is important to select the universal testing machine in such a way so as not to work in the lower part of its range and not to exceed it. During the authors own experimental tests, two MTS universal testing machines were used, with ranges up to 100 kN and equipped with high temperature chambers (to 1400 °C) 25 kN.

An important parameter observed during strength tests is not only force, but also deformations corresponding to the given load. As standard, universal testing machines can provide records in the force-displacement form. Theoretically, if information on deformations was required, based on holder displacement, it is enough to divide the given increase by the initial sample length. However, it is an inaccurate method, as displacement data obtained from a universal testing machine contain both displacement of the sample's measurement and mounting parts—deformations of jaws, holders, etc. Therefore, in order to obtain accurate information on sample deformations, it is necessary to, e.g. affix a tensometer, use an extensometer or the ARAMIS optical measurement system.

However, the issue of measuring deformations arises when testing is conducted in a high temperature chamber: it can be ignored, as did the authors of paper [10], where only information from a universal testing machine were used, or the problem can be solved in two ways:

- the first method is using a special chamber with an observation port so that the sample can be monitored with a high-resolution camera [6].
- the second is the use of an extensometer, which has outputs leading outside the high temperature chamber [6].



Fig. 6.14 Experimental stand with the ARAMIS system and acoustic emissions for measurement of the TBCs systems deformations

- *Digital Image Correlation (DIC) system ARAMIS.*

ARAMIS is a system of contactless, three-dimensional displacements both under static and dynamic loads. Due to the fact that it is a contactless method, it is possible to study elements with complex shapes. In contrast to the tensometer, when using ARAMIS, information on displacements on the entire studied surface of the sample is acquired, while in the case of the tensometer, the information corresponds to its base, i.e. it is localised. Graphical representation of measurement results as coloured fields enables more complete comprehension of the studied object's behaviour.

Based on images taken using digital cameras, ARAMIS recognises the three-dimensional surface structure of the measured object (each pixel in an image is assigned with appropriate coordinates). After recording all images, the system compares them and calculates displacements and deformations.

Figure 6.14 presents the ARAMIS system which was used during own tests in order to accurately determine displacements and deformations at which TBCs systems are damaged. Additionally, AE were used during the tests.

Description of the experimental stand in Fig. 6.14. is as follows: 1—sample with a TBC layer, 2—holders of the universal testing machine, 3—ARAMIS camera system, 4—acoustic emissions sensor.

- *microscopic tests.*

An inseparable element of TBC strength tests is the use of microscopes. Microscopic images can be found in virtually any paper considered in literature, particularly [2, 4, 6–8, 11, 12, 16, 18, 27–33]. However, in most cases they are not used for external observations of the coating's surface, where cracks appear only in

the last phase of TBC damage, but are taken as transverse cross-sections through the layer.

Microscopic images aim to observe the TBC layer structure after:

- it is deposited. It is particularly important when using different powders and different distances of the plasma burner, e.g. as in paper [18], or when using FGM coatings,
- ageing cycles, for different temperatures and ageing times, e.g. as in study [27], where the TGO layer growth is visible, or in paper [32], where columns deposited by EB-PVD are sintered,
- conducting strength tests, e.g. for different loads—a good example is paper [7], where exactly the same area was observed.

Information of this kind is highly valuable, as it forms the basis for correct description of the material model in the ABAQUS program, and consequently performing reliable simulations that are true to reality.

6.2 Conclusions

In the summary, one must agree with the authors of papers [2, 34] that currently there are no standardised test methods and procedures of testing strength properties of TBCs systems.

References

1. Pfeiffer C, Affeldt E, Göken M (2011) Miniaturized bend tests on partially stabilized EB-PVD ZrO_2 thermal barrier coatings. *Surf Coat Technol* 205:3245–3250
2. Zhao PF, Li XD, Shang FL, Li CJ (2011) Interlamellar cracking of thermal barrier coatings with TGOs by non-standard four-point bending tests. *Mater Sci Eng A* 528:7641–7647
3. Arai M, Okajima Y, Kishimoto K (2007) Mixed-mode interfacial fracture toughness for thermal barrier coating. *Eng Fract Mech* 74:2055–2069
4. Guo PQ, Mumm DR, Karlsson AM, Kagawa Y (2005) Measurement of interfacial shear mechanical properties in thermal barrier coating systems by a barb pullout method. *Scr Mater* 53:1043–1048
5. Tassini N, Lambrinou K, Mircea I, Bartsch M, Patsias P, Van der Biest O (2007) Study of the amplitude-dependent mechanical behaviour of yttria-stabilised zirconia thermal barrier coatings. *J Eur Ceram Soc* 27:1487–1491
6. Aleksanoglu H, Scholz A, Oechsner M, Berger C, Rudolphi M, Schütze M, Stamm W (2013) Determining a critical strain for APS thermal barrier coatings under service relevant loading conditions. *Int. J. Fatigue* 53:40–48
7. Wakui T, Malzbender J, Steinbrech RW (2006) Mechanical testing of thermally stressed materials with rough interfaces: mechanically induced delamination cracking in thermal barrier composites. *Surf Coat Technol* 200:5419–5426
8. Yamazaki Y, Schmidt A, Scholz A (2006) The determination of the delamination resistance in thermal barrier coating system by four-point bending tests. *Surf Coat Technol* 201:744–754

9. Bouzakis KD, Lontos A, Michailidis N, Knotek O, Lugscheider E, Bobzin K, Etzkorn A (2003) Determination of mechanical properties of electron beam-physical vapor deposition-thermal barrier coatings (EB-PVD-TBCs) by means of nanoindentation and impact testing. *Surf Coat Technol* 163–164:75–80
10. Mao WG, Dai CY, Yang L, Zhou YC (2008) Interfacial fracture characteristic and crack propagation of thermal barrier coatings under tensile conditions at elevated temperatures. *Int J Fract* 151:107–120
11. Qiana L, Zhua P, Kagawaa Y, Kubob T (2003) Tensile damage evolution behavior in plasma-sprayed thermal barrier coating system. *Surf Coat Technol* 173:178–184
12. Zhou YC, Tonomori T, Yoshida A, Liu L, Bignall G, Hashida T (2002) Fracture characteristics of thermal barrier coatings after tensile and bending tests. *Surf Coat Technol* 157:118–127
13. Li CJ, Wang WZ, He Y (2003) Measurement of fracture toughness of plasma-sprayed Al_2O_3 coatings using a tapered double cantilever beam method. *J Am Ceram Soc* 86:1437–1439
14. Zhang H, Li DY (2005) Application of a novel lateral force-sensing microindentation method for evaluation of the bond strength of thermal sprayed coatings. *Surf Coat Technol* 197:137–141
15. Ciszewski A, Radomski T (1989) Structural materials in mechanical engineering. PWN, Warszawa (in Polish)
16. Wang X, Tint P, Chiu M, Atkinson A (2012) Stiffness of free-standing thermal barrier coating top coats measured by bending tests. *Acta Mater* 60:3247–3258
17. Evans AG, Mumm DR, Hutchinson JW, Meier GH, Pettit FP (2001) Mechanisms controlling the durability of thermal barrier coatings. *Prog Mater Sci* 46:505–553
18. Li Y, Khor KA (2002) Mechanical properties of the plasma-sprayed $\text{Al}_2\text{O}_3\text{YZrSiO}_4$ coatings. *Surf Coat Technol*. 150:143–150
19. Johnson CA, Ruud JA, Bruce R, Wortman D (1998) Relationships between residual stress, microstructure and mechanical properties of electron beam-physical vapor deposition thermal barrier coatings. *Surf Coat Technol* 108–109:80–85
20. Żórawski W (2009) Residual stresses in thermal sprayed coatings. In: *Welding Technology Review*, vol. 9, pp 63–70 (in Polish)
21. Choi PR, Zhu D, Miller RA (2005) Fracture behavior under mixed-mode loading of ceramic plasma-sprayed thermal barrier coatings at ambient and elevated temperatures. *Eng Fract Mech* 72:2144–2158
22. Ray AK, Roy N, Kar A, Ray AK, Bose PC, Das G, Sahu JK, Das DK, Venkataraman B, Joshi PV (2009) Mechanical property and characterization of a NiCoCrAlY type metallic bond coat used in turbine blade. *Mater Sci Eng A* 505:96–104
23. Qian G, Nkamura T, Berndt CC, Leigh PH (1997) Tensile toughness test and high temperature fracture analysis of thermal barrier coatings. *Acta Mater* 45:1767–1784
24. Cao NY, Kagawa Y, Liu YF (2008) Stress analysis of a barb test for thermal barrier coatings. *Surf Coat Technol* 202:3413–3418
25. Eberl C, Gianola DP, Wang X, He MY, Evans AG, Hemker KJ (2011) A method for in situ measurement of the elastic behavior of a columnar thermal barrier coating. *Acta Mater* 59:3612–3620
26. Wen PF, Yan WZ, Kang JX, Liu J, Yue ZF (2010) Simulation of the interface characterization of thin film on substrate system by bending creep tests. *Appl Surf Sci* 257:1289–1294
27. Mao WG, Dai CY, Zhou YC, Liu QX (2007) An experimental investigation on thermo-mechanical buckling delamination failure characteristic of air plasma sprayed thermal barrier coatings. *Surf Coat Technol* 201:6217–6227
28. Park JH, Kim JP, Lee KH (2007) Acoustic emission characteristics for diagnosis of TBC damaged by high-temperature thermal fatigue. *J Mater Process Technol* 187–188:537–541
29. Yao WB, Dai CY, Mao WG, Lu C, Yang L, Zhou YC (2012) Acoustic emission analysis on tensile failure of air plasma-sprayed thermal barrier coatings. *Surf Coat Technol* 206:3803–3807

30. Jadhav AD, Padture NP (2008) Mechanical properties of solution-precursor plasma-sprayed thermal barrier coatings. *Surf Coat Technol* 202:4976–4979
31. Mumm DR, Watanabe M, Evans AG, Pfendner JA (2004) The influence of test method on failure mechanisms and durability of a thermal barrier system. *Acta Mater* 52:1123–1131
32. Yan J, Leist T, Bartsch M, Karlsson AM (2008) On cracks and delaminations of thermal barrier coatings due to indentation testing: experimental investigations. *Acta Mater* 56:4080–4090
33. Zhao PF, Sun CA, Zhu XY, Shang FL, Li CJ (2010) Fracture toughness measurements of plasma-sprayed thermal barrier coatings using a modified four-point bending method. *Surf Coat Technol* 204:4066–4074
34. Vasinonta A, Beuth JL (2001) Measurement of interfacial toughness in thermal barrier coating systems by indentation. *Eng Fract Mech* 68:843–860

Chapter 7

Proposed Experimental Investigations of TBCs Systems

7.1 Sample Ageing

One of the phenomena occurring in TBCs during their operation is the appearance of an Al_2O_3 layer, referred to as TGO in literature. Its occurrence is related to the presence of coating surface porosity, and consequently with the possibility of oxygen accessing the boundary between top coat (TC) and BC. One of the elements comprising the bond coat is aluminium. Therefore, oxygen that penetrates into a TBC system causes the formation of a thin (several micrometres) layer of aluminium oxide, whose thickness gradually increases in time.

TGO layer growth is a slow process. Analysis of literature indicates that authors use ageing times from several tens even up to several thousand hours, i.e. as long as a turbine engine blade service life lasts.

Tested samples (Fig. 7.1) had TBCs systems introduced by APS technology with application of the YSZ in industrial conditions. Thickness of the TC layer was equal to 300 μm , whereas the BC layer had 150 μm . Substrate was made of acid-resisting steel 0H18N9 of the thickness 2 mm. The material data are included in Table 6.1.

One goal of the tests performed for this monograph was to determine the effects of sample ageing time, and consequently of TGO layer growth on TBC system damage.

Sample ageing was performed for four ranges: 48, 89, 185 and 353 h at a temperature of 1000 °C. Ageing was performed using a muffle furnace, whose interior—including the arrangement of samples—is visible in Fig. 7.1. Eight samples of each of the following categories were subjected to ageing: dumbbell, beam and cylinder. Samples were removed from the furnace, after the specified times had passed, only after it had cooled completely, in order to prevent sudden thermal shocks.

Fig. 7.1 Arrangement of samples in a muffle furnace



7.2 Uniaxial Stretching of Dumbbell Samples with TBC Layers—Author's Own Tests

Uniaxial sample stretching is one of the most commonly performed tests when determining strength parameters of a TBC system. The tests were to determine critical deformations leading to TBC system damage, both for coatings in their original state and subjected to ageing. Tests were conducted for two batches of samples:

1. results from the first batch were to provide information concerning critical deformations lead to cracks initiation in TBCs,
2. the second sample batch was stretched only to a certain load level (determined using the results from the first batch), and subsequently, microscopic observations were performed.

7.2.1 First Batch of Samples Not Subjected to Ageing

Tests were performed using a MTS 100 kN testing machine. A sample, placed in the universal testing machine's holders, is presented in Fig. 7.2. The rate of stretching applied to all samples was 0.2 mm/min.

The first batch of samples was stretched until visible cracks appeared, clearly indicating that the coating had been damaged. However, analysis of literature performed earlier indicates TBC system damage begins at the interface between TC and BC, which is invisible to the naked eye.

For this reason, in order to determine the critical deformations at which cracks initiation occurs, two methods were employed:

- the use of the ARAMIS system,
- the use of acoustic emissions (AE).

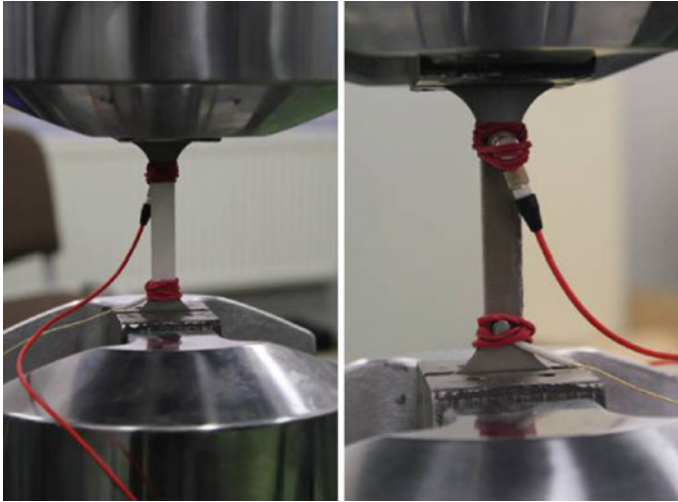


Fig. 7.2 Sample with acoustic emissions sensors attached

Figure 7.3 presents two images of deformations in a TBC system during uniaxial tension of a sample not subjected to ageing:

- (a) for a load equivalent to the substrate material's yield point ($\sigma_y = 6.2$ kN),
- (b) after exceeding the yield limit, when the material starts to strengthen (7.2 kN).

In the first case, it is impossible to notice changes in deformation fields; second, brighter lines become appear, indicating cracks propagation. When observing the sample with a naked eye (Fig. 7.4), coating cracks can be seen starting from loads of 7.8 kN.

A more effective method of determining when the damage begins to appear is AE, as it enables registering cracking process that are not visible on the coating's surface. Figure 7.5 presents results both for samples not subjected to ageing and for samples after ageing. In samples not subjected to ageing process, the first visible AE amplitude occurs at 6.8 kN load, so AE, in the case of brittle materials and TBCs, enables earlier detection of the crack initiation moment.

The results obtained in the first batch of samples narrowed down the tensile load level to 5 kN, after which microscopic observations were performed.

7.2.2 Second Batch of Samples Subjected to Ageing

In the second batch of tests samples were subjected to ageing process and further to mechanical loads, like in the first batch. Moreover, we performed SEM observations of TBC systems on a FEI QUANTA FEG 250.

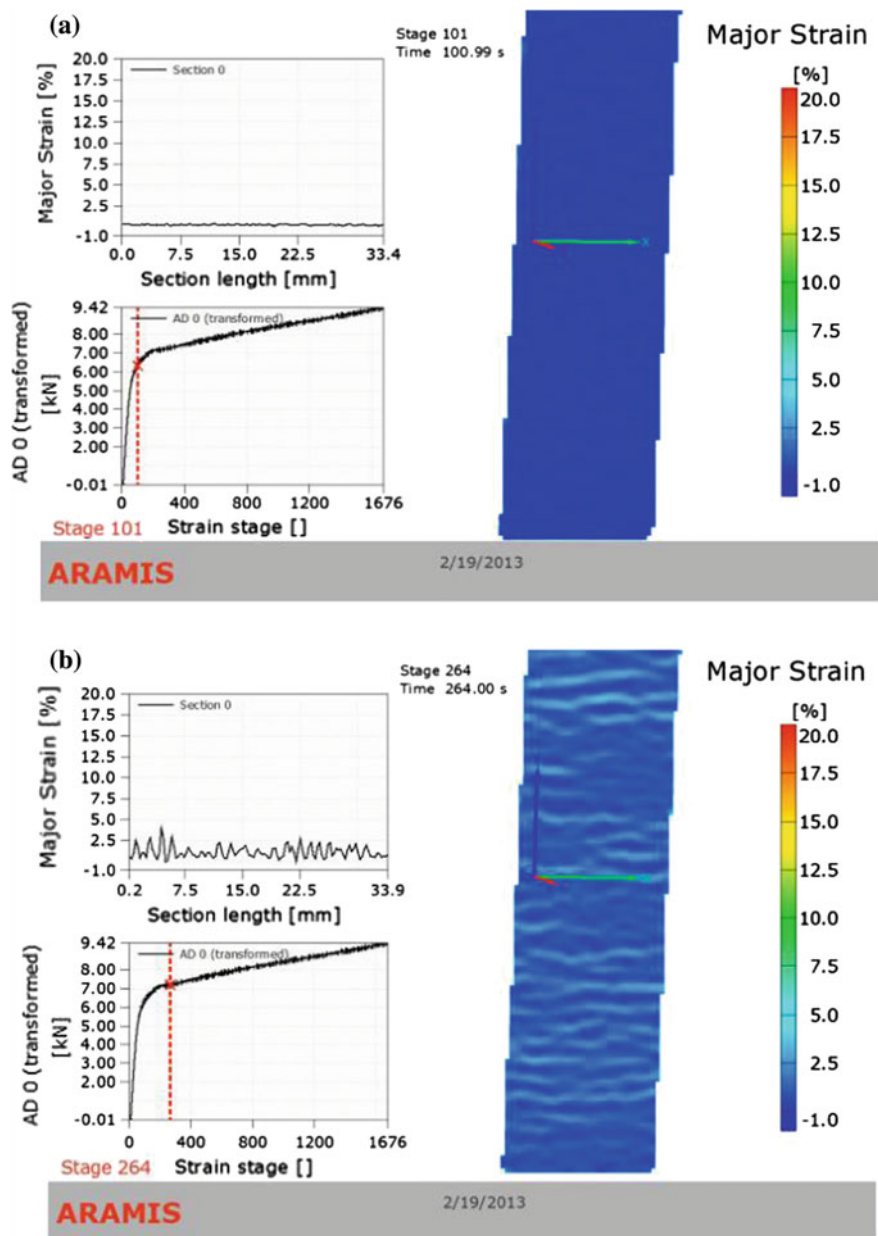


Fig. 7.3 Main deformation (vertical direction) in samples, monitored using the ARAMIS system: **a** before damage is initiated, **b** after damage is initiated

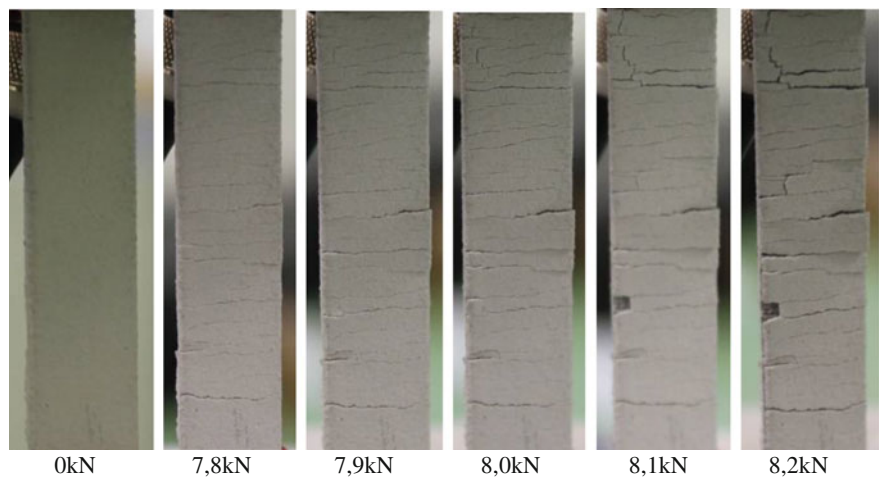


Fig. 7.4 Initial stage of a TBC system damage during single-axis stretching

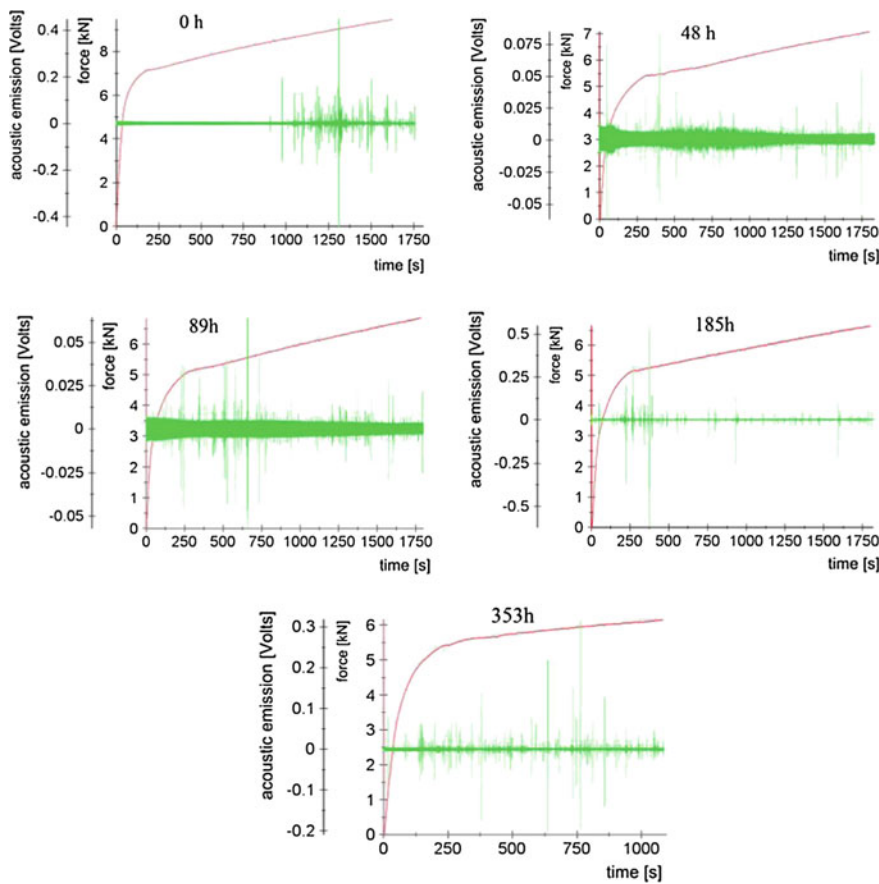


Fig. 7.5 Acoustic emissions result for stretched samples

Microscopic tests concerned samples with a TBC layer subjected to ageing in a furnace at 1000 °C. Ageing times were: 48, 89, 185 and 353 h, respectively. Subsequently, samples were subjected to stretching by applying a load of $5 \text{ kN} < \sigma_y$ in each case. The same load was also applied to the sample that was not subjected to the effects of ageing.

Before the SEM tests fragments of dumbbell samples after tensile tests were cut and encased in resin as per the procedure presented in Fig. 7.6 to show the internal structures of TBCs.

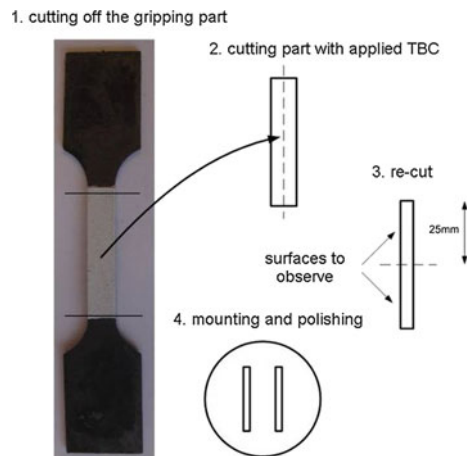
Analysing the images, (Fig. 7.7), taken using the SEM, the following layers can be distinguished: TC, approx. 300 μm thick; bond coat (BC), 150 μm thick and the metallic layer.

The layer not subjected to ageing has single cracks resulting from merging of pores present in the ceramic layer.

Even after a small number of hours that the sample spent in an aggressive environment, and subjecting it to a mechanical load, it can be noted that there is one primary crack. It is situated in the ceramic layer, right next to the boundary with the bond coat. In certain places and for large magnifications, cracking at the boundary of the two layers could be noticed (Fig. 7.8). However, transverse or edge cracks were not noted in the sample. After 89 h of annealing, the same damage mechanism still exists. However, in places, the crack is starting to migrate, from the BC boundary even to several tens of micrometres within the ceramic layer.

Figure 7.7d presents a fragment from the sample's middle section (considering its length), for which the ageing time was 185 h. Both a horizontal crack, of significant size—more than 10 micrometres, and a vertical crack are visible. These phenomena indicate deteriorating strength properties of the TBC system.

Fig. 7.6 Sample preparation for testing



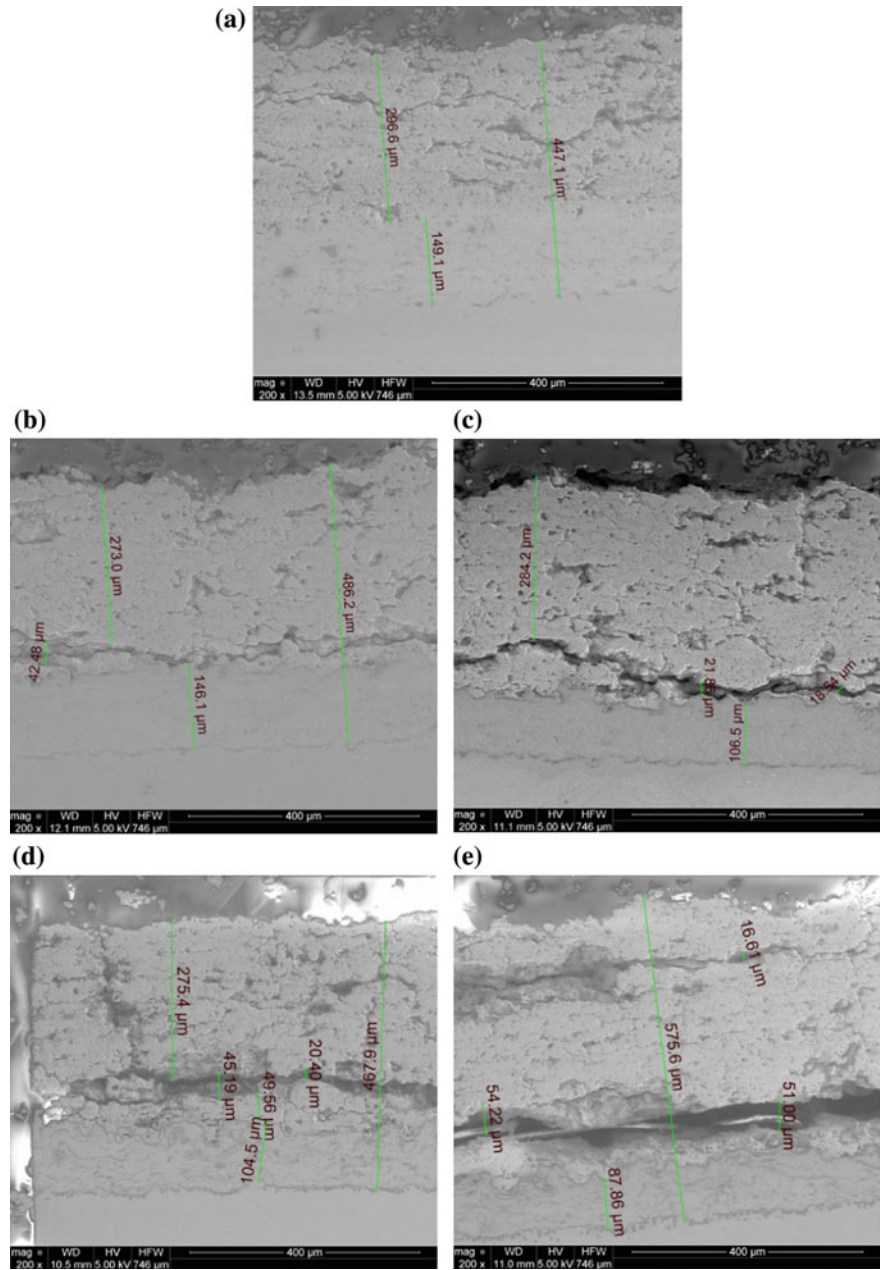
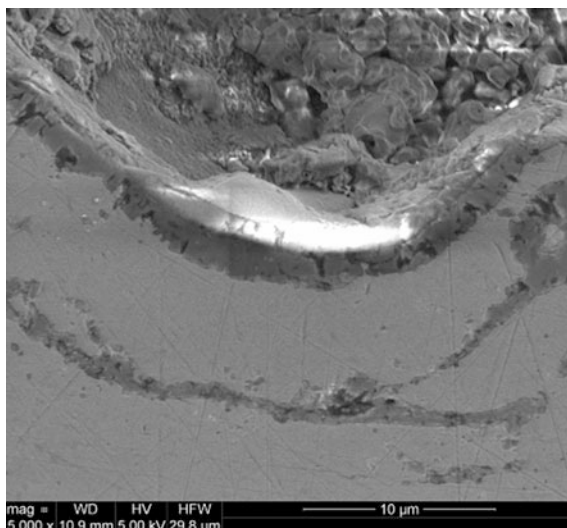


Fig. 7.7 Images of the TBC layer with dimensions for different ageing times. **a** 0 h. **b** 48 h. **c** 89 h. **d** 185 h. **e** 353 h

Fig. 7.8 Crack at the TC and BC interface (89 h)



The damage area for 353 h is presented in Fig. 7.7e. The crack thickness at the BC boundary is now in the order of 50 μm . A horizontal crack in the upper part of the ceramic layer can also be clearly seen. However, in no cases was damage in the BC or at the BC and substrate interface observed.

Another important phenomenon that occurs during the operation of blades with TBCs is the appearance of the aluminium oxide Al_2O_3 layer, referred to in literature as TGO.

Figure 7.9a presents the ceramic TBC layer and the substrate. For samples not subjected to ageing, there are no visible boundaries between the layers mentioned above. Even after 48 h of ageing, a boundary in the form a dark “stripe” running across the entire length of the sample can be observed, Fig. 7.9b. After performing a chemical analysis, the presence of two main elements was noted: oxygen and aluminium. It indicates that a Al_2O_3 had formed at the boundary. The thickness of this layer increases in time, which is presented on the chart (Fig. 7.10), where a logarithmic function describing the TGO thickness growth has been matched. This data must be taken very cautiously as it originates from only one sample cross section.

The SEM also has the ability to perform EDS (energy dispersive spectroscopy) X-ray microanalysis. Reading the intensity of characteristic X-ray radiation is possible, thanks to the formation of electron-hole pairs. EDS analysis was performed for samples subjected to ageing and in such layers as TC, TGO, BC, BC-metal interface and metal.

In the ceramic TC layer, the main elements are: oxygen 56.48–63.19 % and zirconium 29.54–31.86 % (Table 7.1). The third element is yttrium 2.86–4.49 %. This indicates the presence of ZrO_2 stabilised by Y_2O_3 .

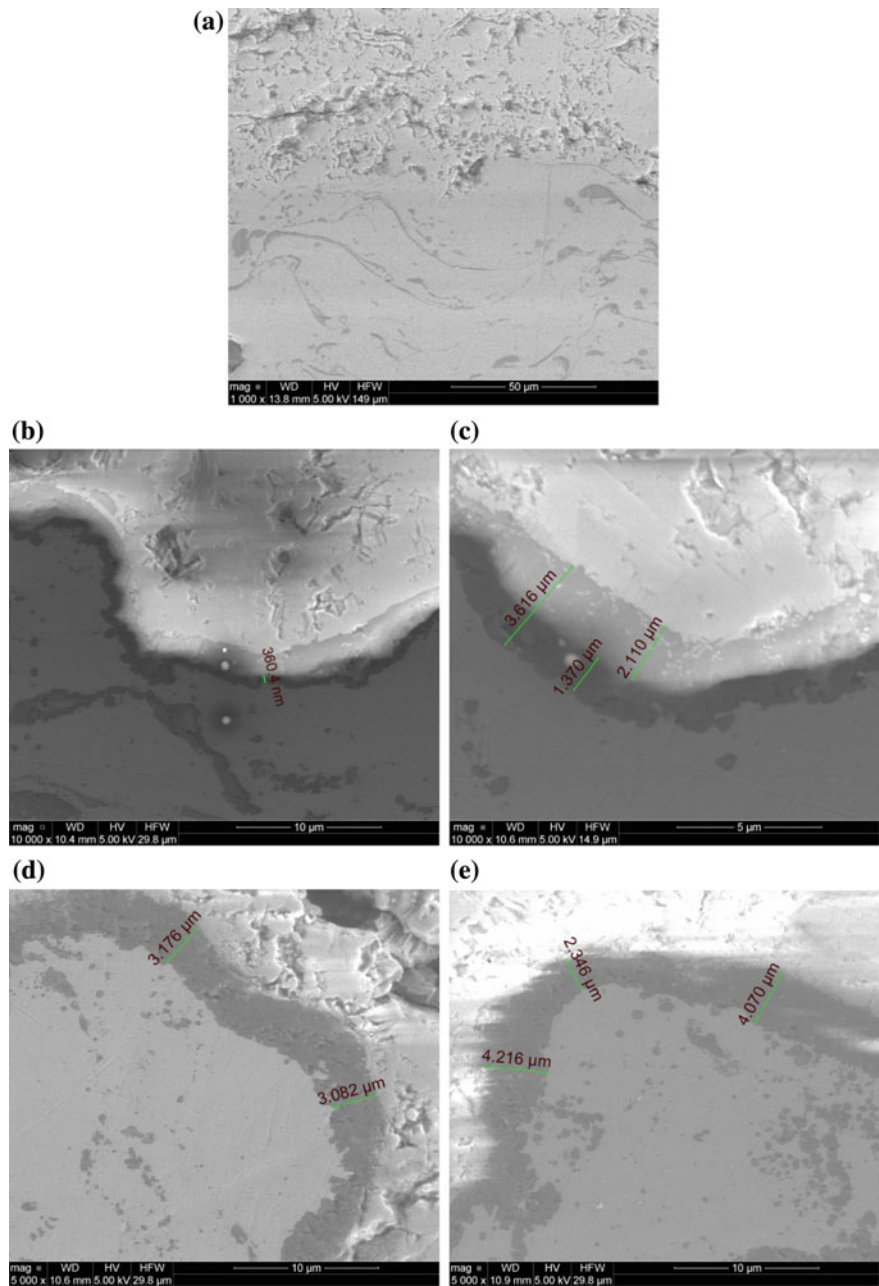


Fig. 7.9 TGO layer dimensions for different ageing times. **a** 0 h. **b** 48 h. **c** 89 h. **d** 185 h. **e** 353 h

Fig. 7.10 Function describing the TGO layer growth

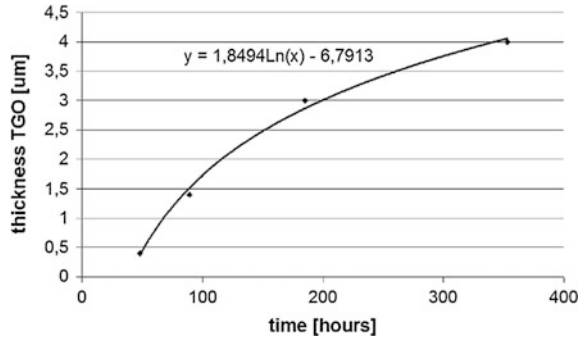


Table 7.1 Element content—TBC layer

	O	Al	Y	Zr	Cr	Fe	Co	Ni
48 h	56.48	1.36	3.21	31.86	1.45	1.86	1.18	2.27
89 h	57.08	1.50	3.35	31.14	1.39	2.03	0.99	2.28
185 h	51.59	0.70	4.49	36.29	1.38	1.94	0.84	1.47
353 h	63.19	0.72	2.86	29.54	0.81	1.55	0.32	0.79

The remaining elements, whose content is at a level of 1 %, are the result of diffusion from deeper layers, which is not intensive at high temperatures.

The detection of the TGO layer (Table 7.2) was extremely important, as this layer was distinguished by a different shade of grey at the ceramic layer boundary which made locating it easier. This layer contained from 49.52 to 58.90 % oxygen and 32.35 to 41.35 % aluminium. This confirmed the presence of Al₂O₃. The content of other elements is at a level of one to several percent.

The third layer is BC (Table 7.3). It is a layer where such elements as Ni, Co, Cr, Al and Y should be found, in the order from the highest to the lowest content. Analysis confirms the presence of the elements listed above and in the same order of percentage content. Additionally, zirconium and iron are found in this layer. Both these elements originate from diffusion from neighbouring layers. For ageing times 185 and 353 h, oxygen content in the bond coat drops to a few percent; this occurs as a result of growth of the ever thicker and tighter TGO layer.

Table 7.2 Element content—TGO layer

	O	Al	Y	Zr	Cr	Fe	Co	Ni
48 h	57.95	32.35	0.21	2.57	1.44	1.00	1.29	2.59
89 h	58.90	34.45	0.21	1.10	1.22	0.98	0.98	2.06
185 h	51.86	41.35	0.65	1.96	1.08	0.93	0.73	1.43
353 h	49.52	33.04	0.56	4.29	1.37	1.37	3.53	6.31

Table 7.3 Element content—BC layer

	O	Al	Y	Zr	Cr	Fe	Co	Ni
48 h	27.05	13.11	0.43	3.03	17.92	2.60	22.01	4.49
89 h	24.02	8.81	0.27	1.92	13.91	4.41	15.81	29.10
185 h	5.59	11.85	0.22	2.21	17.41	5.64	19.55	37.52
353 h	4.32	27.30	0.19	1.77	6.38	7.46	9.52	43.04

Source Author’s own tests

Table 7.4 Element content—BC–metal boundary

	O	Al	Y	Zr	Cr	Fe	Co	Ni
48 h	6.06	60.07	0.05	1.56	6.69	13.35	3.97	8.25
89 h	8.49	64.17	0.11	2.07	5.06	9.71	3.30	7.04
185 h	1.78	75.96	0.20	2.02	4.20	7.51	2.63	5.71
353 h	1.20	78.19	0.10	2.73	3.73	7.61	1.85	4.58

Source Author’s own tests

An interesting place is the vicinity of the BC–metal interface (Table 7.4). During ageing, the appearance of a new phase can be observed, which—at low magnifications—clearly forms a boundary.

However, it is not continuous and does not have a uniform thickness, as is the case with TGO, but is formed by individual grains, sized more than 10 μm (Fig. 7.11). After performing the EDS analysis it was concluded that this layer contains 60–78 % aluminium, and the rest is mainly iron and nickel from the metallic layer.

The last layer is the metallic substrate. It was the 0H18N9 stainless steel with a theoretical chromium content of 17–19.5 % and nickel 8–11 %. While chromium

Fig. 7.11 Bond coat-metal boundary (353 h)

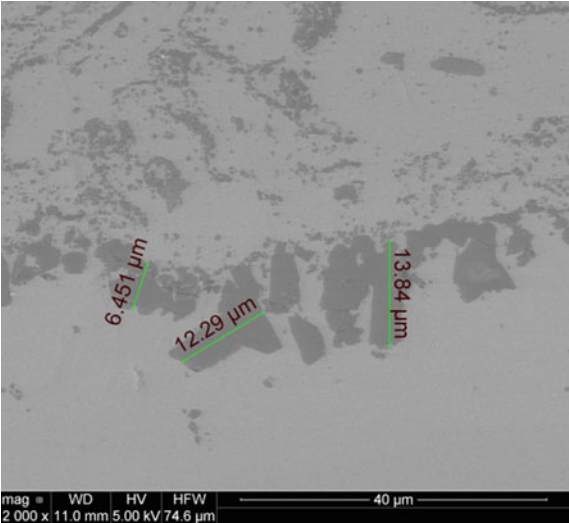


Table 7.5 Element content—substrate

	O	Al	Y	Zr	Cr	Fe	Co	Ni
48 h	2.80	1.26	0.11	1.36	18.34	56.02	4.63	15.48
89 h	7.77	2.07	0.09	1.56	16.93	42.88	8.20	20.48
185 h	0.21	2.41	0.13	1.23	17.70	41.42	11.05	25.84
353 h	0.19	1.57	0	1.81	17.93	45.21	9.72	23.24

Source Author's own tests

content is at the right level, nickel content is too high, and additionally, cobalt is present (Table 7.5). However, after performing measurements, even at 45 μm from the BC boundary, the content of elements is as expected. Measurements in close proximity indicate therefore the occurrence of diffusion between all layers, Zr and Y, can also be found in the substrate layer.

7.3 3-Point Bending of Beam Samples with TBC Layers—Author's Own Tests

During operation, a blade and its coating experience not only stretching caused by the centrifugal force, but also bending in certain areas located in its bottom part. When testing TBCs, appropriate samples “for bending” had therefore to be prepared. The coating was manufactured on a 2 mm thick 0H18N9 steel substrate. Sample length was 50 mm and width 10 mm.

For such small samples, it was necessary to design and manufacture a special holder presented in Fig. 7.12a. The holder has adjustable supports, so that it is possible to execute both 3-PB and 4-PB. In this case, due to the presence of small loads, an MTS testing machine with a range of capacity up to 25 kN.

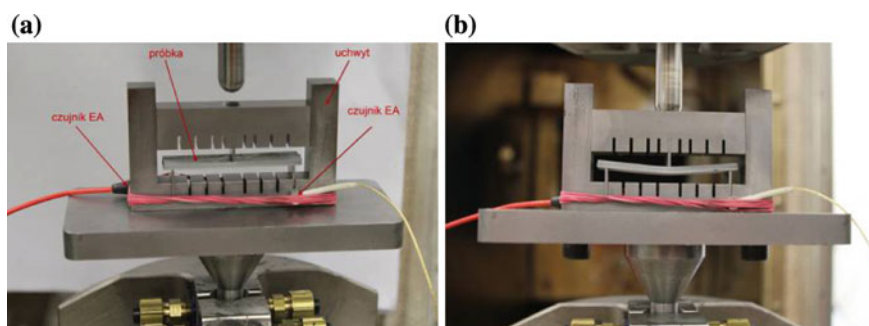


Fig. 7.12 **a** Holder with a mounted sample, **b** deformed sample after 3-PB test

All tests were performed at room temperature. Similarly as in the case of samples for stretching, some of them were subjected to ageing at 1000 °C for periods of 48, 89, 185 and 353 h, respectively.

After performing bending for the first, non-aged sample, two characteristic deflections of the sample were determined: 0.8 and 2 mm. In this case, the load constituted the holder beam displacement by a set value. The test was performed at a rate of 0.2 mm/min.

Figure 7.12b presents an image of a deformed sample after the test. In order to identify the load for which the first cracks may appear, AE, and two sensors were used. The sensors were placed in the bottom part of the holder, on both sides.

Results in the form of charts: force–time and AE–time are presented in Fig. 7.13. When analysing the above charts, it can be noted that for the 0.8 mm displacement, high AE amplitudes can only be observed for 185 and 353 h ageing. However, microscopic observations, whose description is provided later in the section, indicate that cracks also occurred for shorter ageing times. A conclusion can therefore be formulated that the use of AE sensors in the lower part of the holder does not guarantee registering all phenomena occurring during tests. However, in this case, the sensors could not be affixed directly to the sample as they could be damaged.

The sample's mechanical response for the deformation corresponding to 2 mm displacement is important. For the non-aged sample, the emissions did not indicate anything. For aged samples, event saturation increases with the increase of hours the samples were kept in the furnace.

SEM observations of the sample damage caused by 3-PB were also conducted. To this end, the samples were cut apart, encased in resin and polished, as demonstrated in Fig. 7.14.

Totally, 10 samples were observed. Both the sample edge and its central part, where the greatest bending moment occurred, were observed. 200× and 500× magnifications were used. Figure 7.15 presents a summary of images from the microscopic observations.

The presented test results for non-aged samples and set deflection 0.8 mm indicate that no visible edge cracks were observed. However, delamination at the contact of TC and BC layers occurs at the sample's edge.

By extending the ageing process, various phases of damage development at the same set displacement can be observed. For ageing times 48 and 89 h and displacement 0.8 mm, cracking occurs only at the contact of TC and BC layers. For longer times of sample exposure to high temperature (185 and 353 h), TC layer becomes saturated with cracks (Fig. 7.16). Thus formed horizontal cracks have a size of less than 20 µm, regardless of the ageing time.

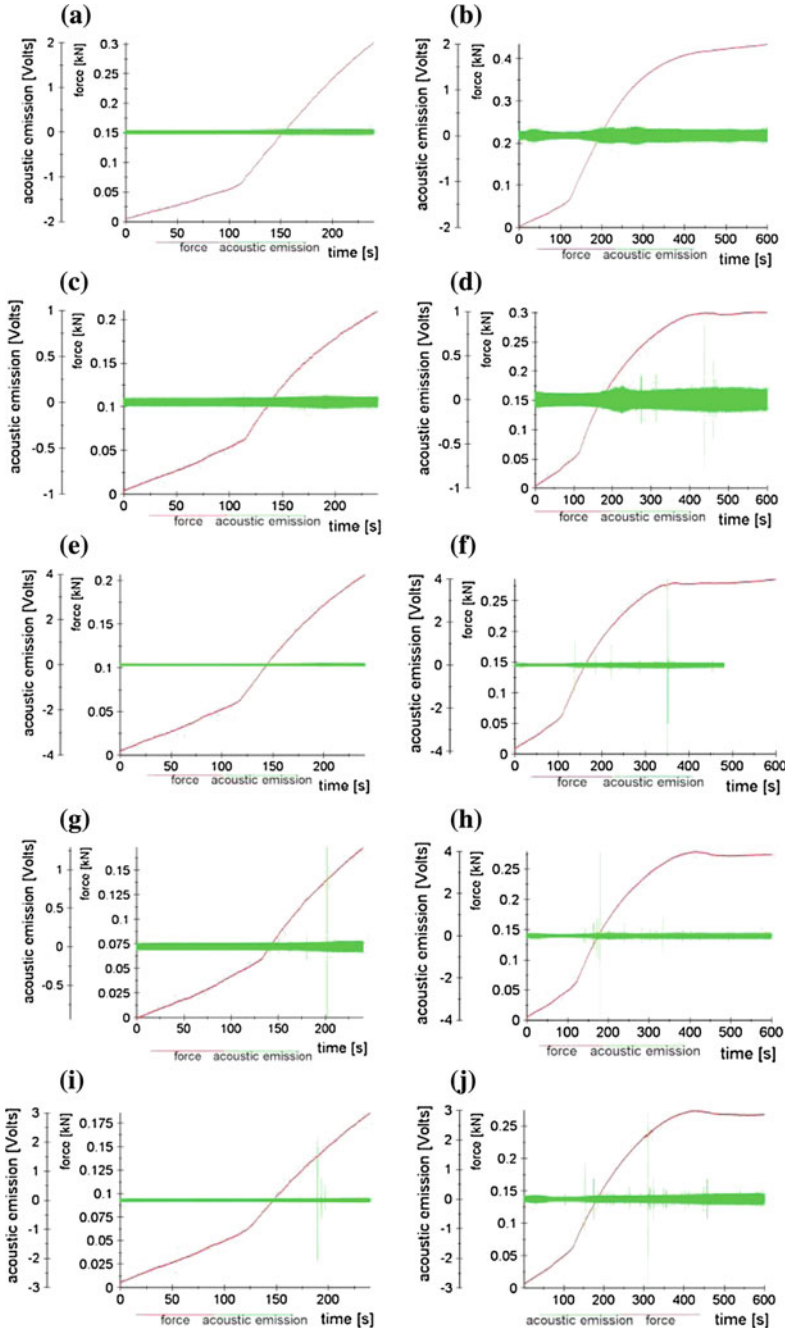


Fig. 7.13 Summary of acoustic emissions results. **a** 0 h and 0.8 mm. **b** 0 h and 2 mm. **c** 48 h and 0.8 mm. **d** 48 h and 2 mm. **e** 89 h and 0.8 mm. **f** 89 h and 2 mm. **g** 185 h and 0.8 mm. **h** 185 h and 2 mm. **i** 353 h and 0.8 mm. **j** 353 h and 2 mm

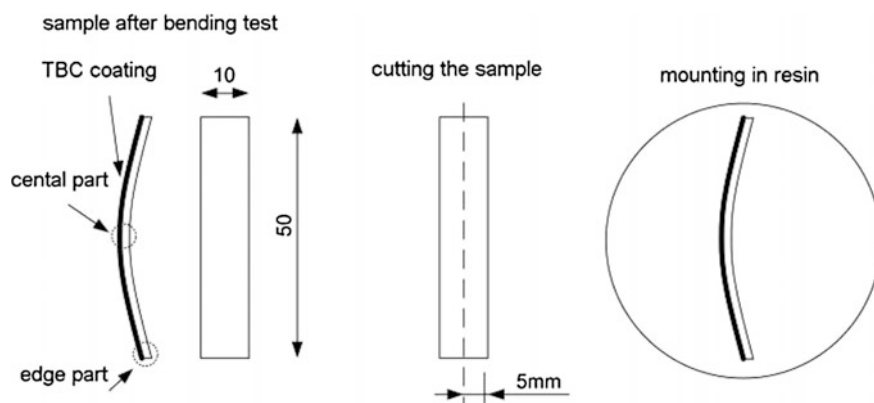


Fig. 7.14 Sample preparation for microscopic tests

Completely different effects are observed for a set deflection of 2 mm. With this deformation and for a sample not subjected to ageing, vertical edge cracks appear in the central part, with a width of more than 10 to several 10 of μm . They run both through the TC and BC layers, reaching the substrate (Fig. 7.17a). The forming vertical edge cracks are not accompanied by horizontal cracks at the TC–BC interface, however. When ageing time is increased to 48 h, two cases of crack formation may occur:

- only through the TC and BC layers (vertical crack),
- along the TC–BC boundary (horizontal crack) and again through the TC and BC layers (vertical crack).

In the second case, the crack takes the “U” shape. “U” cracks form if two vertical cracks occur nearby (Fig. 7.17b).

For the 89 h ageing time, yet another different crack formation model can be distinguished. Both a vertical crack, running through the TC and BC layers, and a horizontal crack along a significant portion of the sample’s length occur (Fig. 7.17c).

For ageing times from 185 and 353 h, a fourth crack formation model exists. It involves a vertical crack reaching only the bond coat, and a greater crack saturation per sample length unit, as well as a series of short horizontal cracks (Fig. 7.17d, e).

In no sample did a case of a horizontal crack at the substrate–BC layer boundary occur. Vertical cracks only run through the BC layer. For ageing times from 185 and 353 h, the ceramic layer and its boundary are weak enough that cracks do not propagate inside the metallic substrate.

Sample deflection 0.8 mm, sample centre, magnification 200 x.

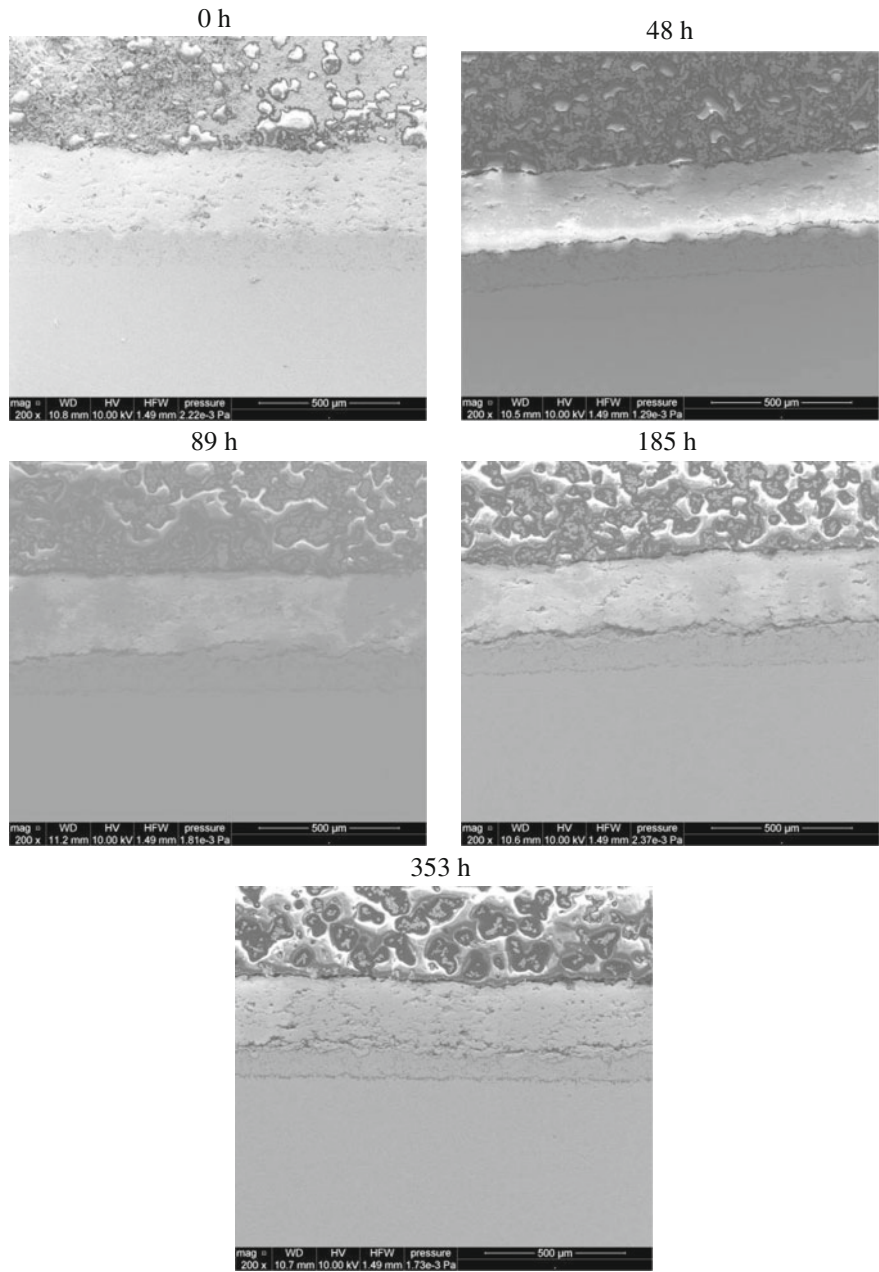


Fig. 7.15 (continued)

Sample deflection 0.8 mm, sample centre, magnification 500 x.

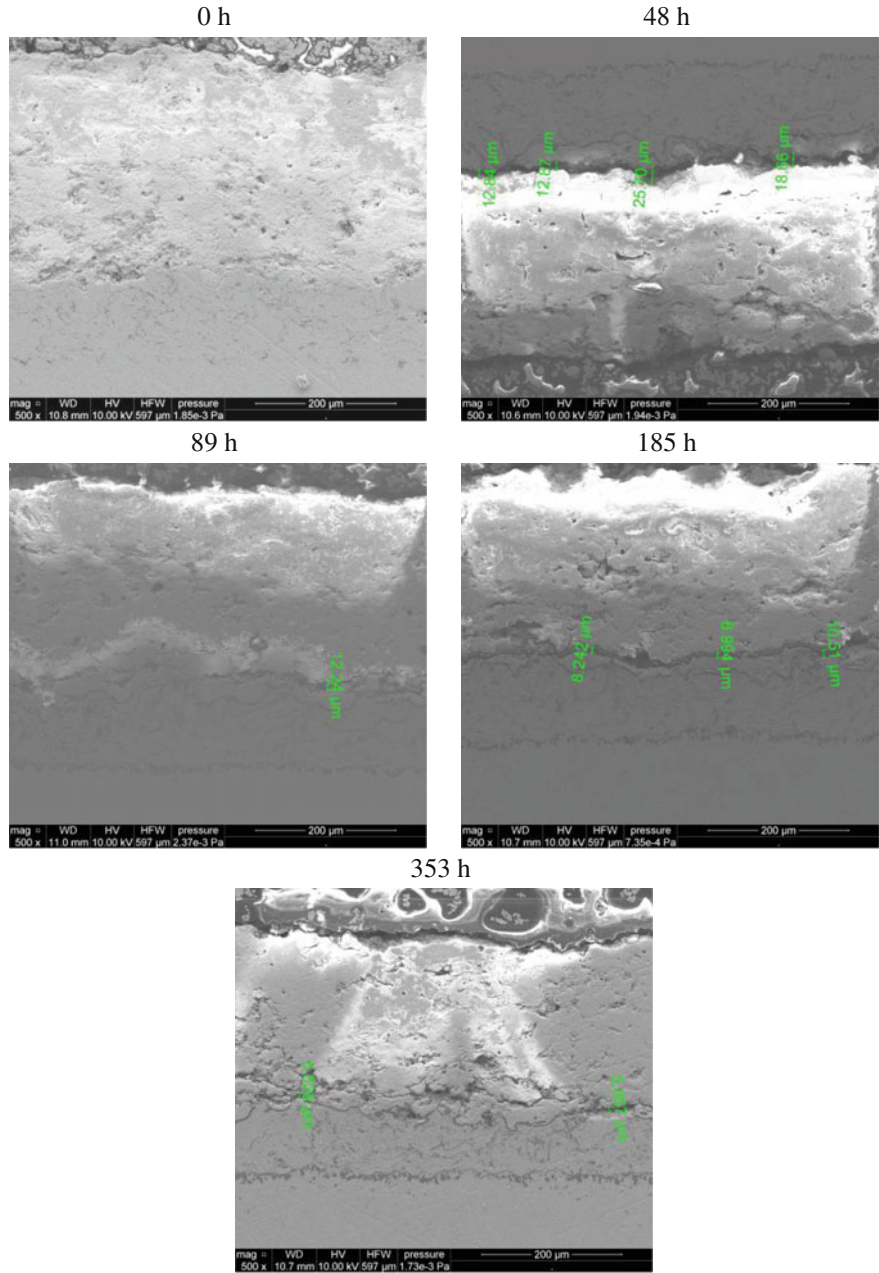
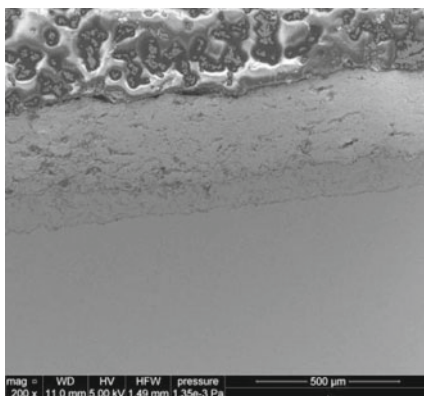
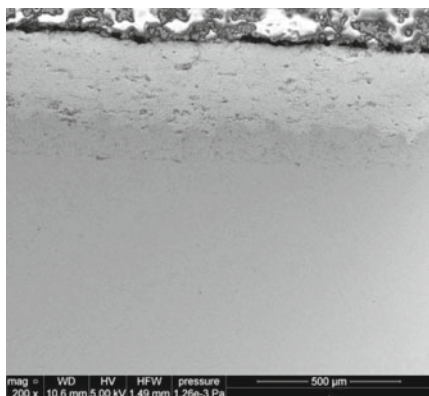


Fig. 7.15 (continued)

Sample deflection 2 mm, sample edge, magnification 200 x.

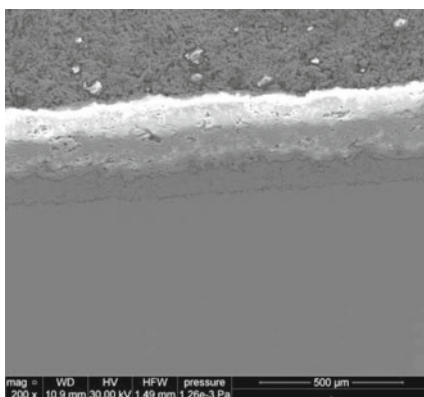
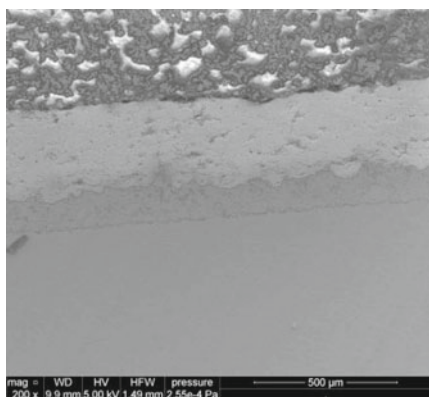
0 h

48 h



89 h

185 h



353 h

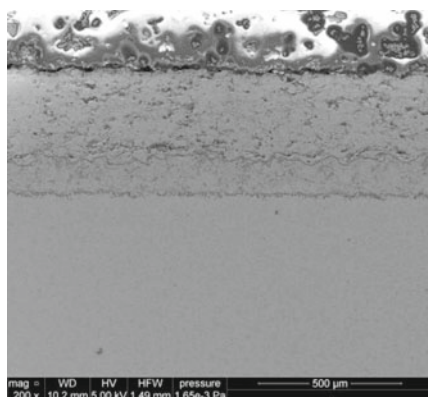


Fig. 7.15 (continued)

Sample deflection 2 mm, sample centre, magnification 200 x.

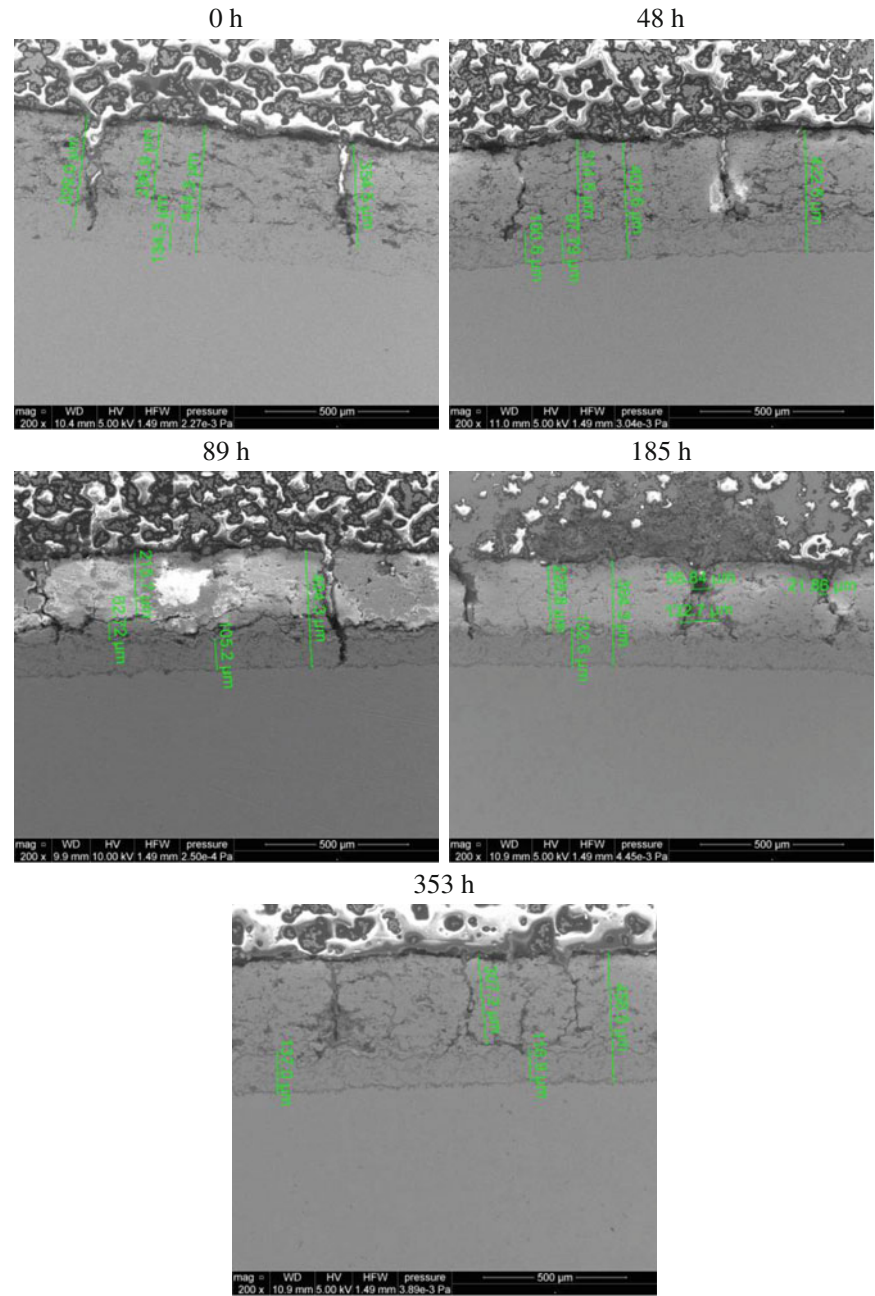


Fig. 7.15 (continued)

Sample deflection 2 mm, sample centre, magnification 500 x.

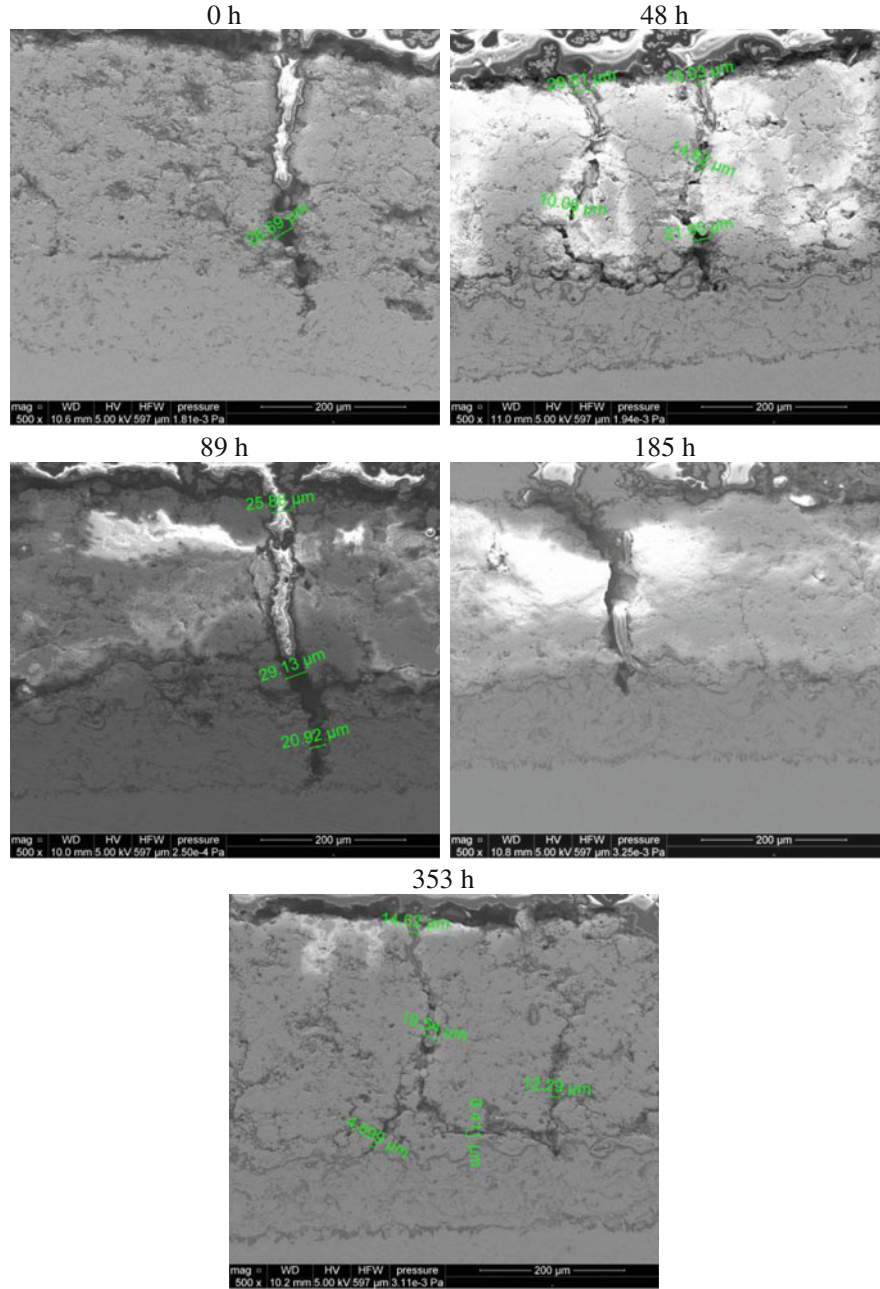


Fig. 7.15 (continued)

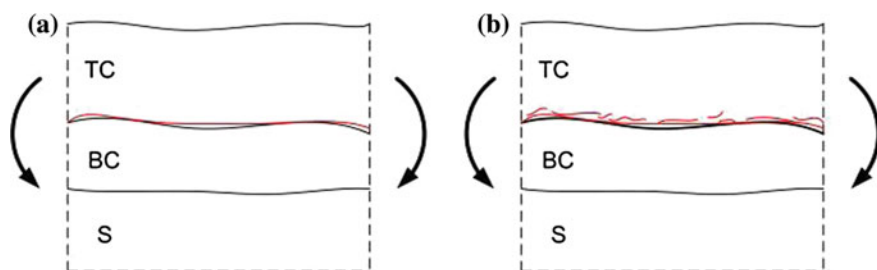


Fig. 7.16 Cracking at the TC–BC boundary for shorter (a) and longer (b) ageing time at the same load

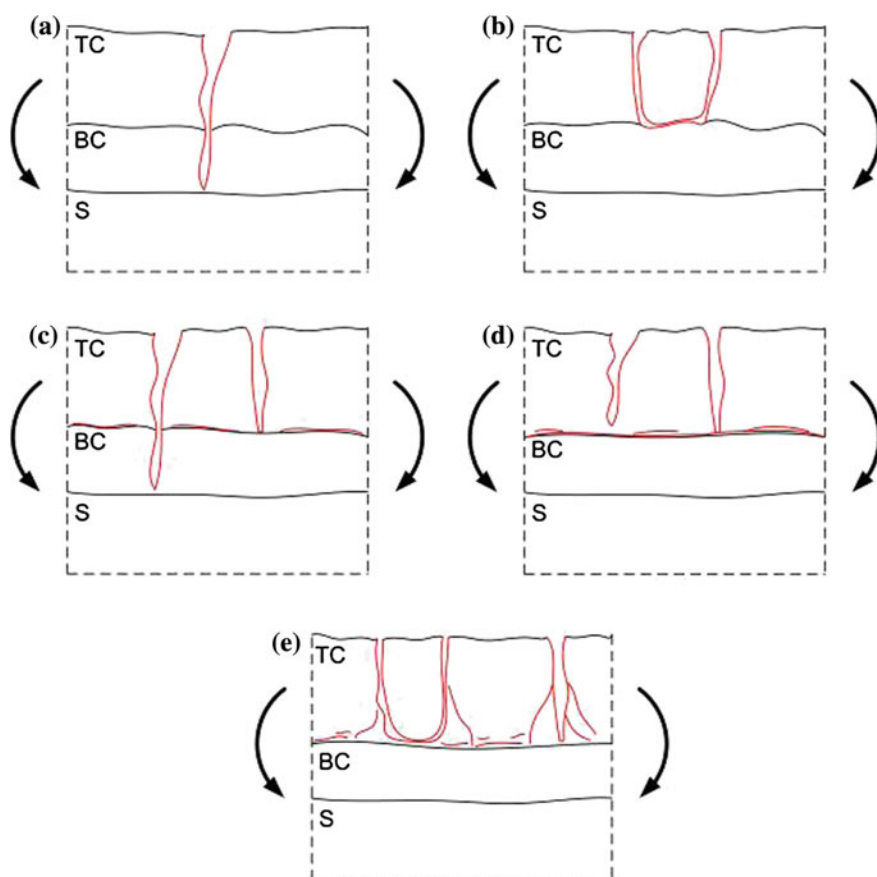


Fig. 7.17 System of cracks corresponding to 2 mm deflection in 3-PB tests, for different ageing times : a 0 h, b 48 h, c 89 h, d 185 h, e 353 h

7.4 Conclusions

To date, there are no uniform procedures or standards that concern testing of the, complex in terms of structure and loads, TBC system. The most rational is performing classic coated samples for stretching and bending. In order to determine the damage, studies on TBC tests must include a section on ageing and microscopic observations.

Chapter 8

Numerical Analysis of Cracks Propagation Process in Turbine Blades TBCs Systems Under Thermo-Mechanical Loading Based on Experimental Results

8.1 Formulation of FEM Approach and Brittle Damage of the TBCs System

In this chapter, we present a numerical method of thermo-mechanical analysis of the TBC systems. It can be used as a simulation of the whole TBCs systems behaviour or as a part of a large simulation as a submodel. Moreover, the method can be applied for calibrating material data that concerns damage evolution laws.

The numerical model is constructed as a section of the dumbbell sample with a length of 2 and 0.1 mm thickness (Fig. 8.1). The internal structure of the TBC is composed of three parts: substrate, BC and TC constituting separate models. Moreover, such modelling method enables setting properties for contacts between the three parts.

The numerical model, formulated in ABAQUS code, was constructed of C3D8R elements: 13,000 for the substrate, 4355 for the BC, and 9015 for the TC (Fig. 8.2).

The experimental results from the previous chapter indicate that deformation process of the TBCs is very complex and different damage mechanisms should be incorporated in the model like:

- edge cracking process of the TC,
- delamination of the TC–BC interface,
- cracking process of the BC.

All these mechanisms should be taken into account. Therefore, the numerical model should describe brittle cracking modes of the TC and BC, whereas delamination of the TC–BC interface or TGO interphase can be described as cohesive surface, Fig. 8.3. Below, we describe the main ideas of both cracking and delamination models.

Fig. 8.1 Structure of the numerical TBC model

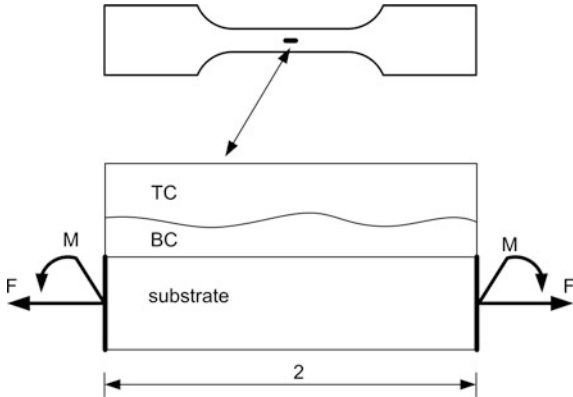


Fig. 8.2 Finite element mesh

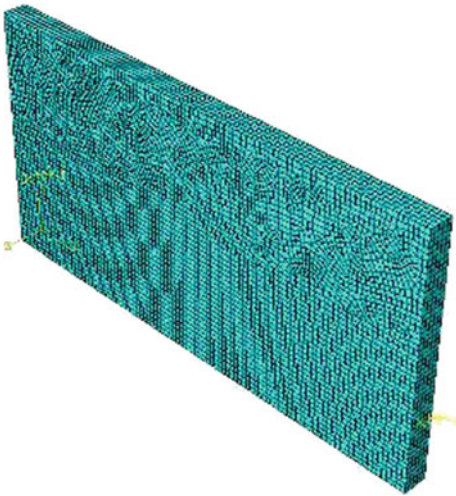
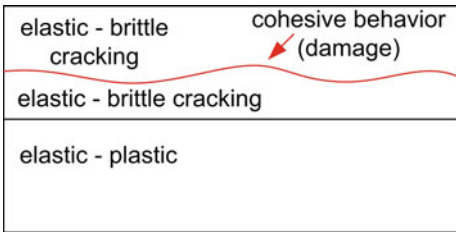


Fig. 8.3 The most advanced model of the TBCs including use of brittle cracking and cohesive surfaces between TC and BC



8.1.1 Brittle Damage Model

The brittle damage and cracking model accessible in ABAQUS/Explicitite enables:

- description of gradual deterioration of brittle materials, such as ceramics and rocks, by introduction of a set of damage parameters for different loading or deformations modes,
- simulation of dominant cracks initiation and growth in materials by removing elements from the mesh.

The brittle damage model is a fuzzy model representing set of discontinuities in brittle material. The occurrence of a set of micro-cracks affects the loading capacity of the material, as well as its stiffness.

Cracks initiation is described on the basis of a simple Rankine hypothesis (Fig. 8.4), which assumes that cracks form when the maximum tensile stresses reach the tensile strength σ_t^I (Mode I). After meeting the criterion, the surface of the formed crack is perpendicular to the tensile stress direction. In the analysed model, cracks may not close and remain until the end of the simulation. However, if stresses change their sign to minus, i.e. we have compression and cracks may close.

Crack evolution can be defined in three ways, in relation to: stress state, fracture energy or displacement state. The following criteria are used to describe the evolution:

- stress—deformation type criterion (Fig. 8.5),
- fracture energy criterion G_f^I (Fig. 8.6)—energy results from Mode I of cracking and is defined directly as material data. Displacement, at which complete loss of material strength occurs, is described using the following formula:

$$u_{n0} = 2G_f^I / \sigma_t^I, \quad (8.1)$$

- critical displacement criterion u_{n0} (Fig. 8.6)—alternatively, fracture energy can be expressed by describing stresses as a function of displacement u_n .

Fig. 8.4 Rankine criterion for the flat state of stress

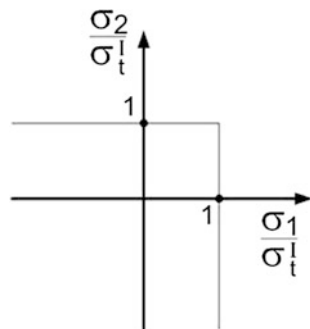


Fig. 8.5 Stress—deformation type criterion

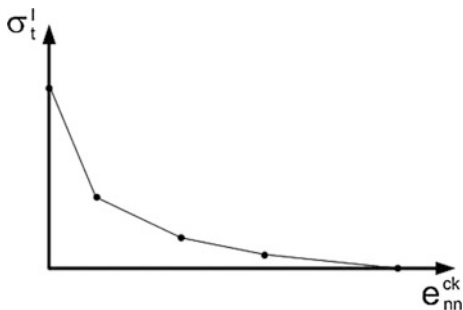
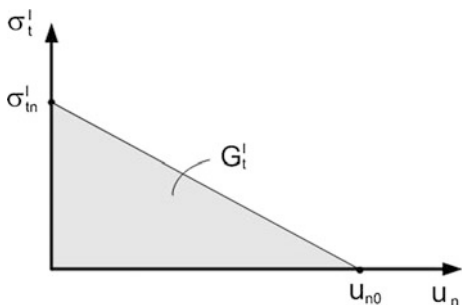


Fig. 8.6 Cracking energy criterion



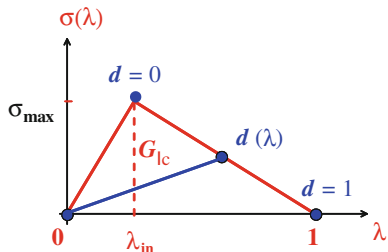
8.1.2 Cohesive Degradation Model

In order to simulate gradual decohesion and the failure process of the interface layer, a CZM model was applied in FEA calculations. Figure 8.7 shows the triangular stress-separation law for the uniaxial case. λ is non-dimensional opening displacement equal to

$$\lambda = \frac{u_n}{\delta^{\max}} \quad (8.2)$$

where u_n is the normal opening displacement and $\delta^{\max}$ is a maximum opening displacement. $\sigma^{\max}$ is the maximum stress threshold for the modelled material, whereas λ_{in} corresponds to the non-dimensional displacement indicating damage initiation in the material.

Fig. 8.7 Stress—displacement rules for CZM with damage parameter d (triangular rule)



G_{Ic} is the area under the curve corresponding to the absorbed energy to fracture. In 3-D cases, where a complex mode of damage growth occurs, it is necessary to introduce a normal opening displacement u_n for the tension mode and a tangential displacement u_τ for the shear mode. Similar to (8.2), it is possible to define non-dimensional displacements λ_n and λ_τ :

$$\lambda_n = \frac{u_n}{\delta_n^{\max}}, \quad \lambda_\tau = \frac{u_\tau}{\delta_\tau^{\max}} \quad (8.3)$$

where $\delta_n^{\max}$, $\delta_\tau^{\max}$ are the maximum opening and shear displacements. We assume for the considered 3-D case that the damage initiation criterion will depend on current state of stress $\{\sigma_n, \sigma_t, \sigma_s\}$ and is expressed as:

$$\left(\frac{\sigma_n}{\sigma_n^{\max}}\right)^2 + \left(\frac{\sigma_t}{\sigma_t^{\max}}\right)^2 + \left(\frac{\sigma_s}{\sigma_s^{\max}}\right)^2 = 1, \quad (8.4)$$

where σ_n is the normal stress to the surface of the adhesive layer, whereas σ_t and σ_s are the shear stress components along the adhesive layer. The values of $\sigma_n^{\max}$, $\sigma_t^{\max}$, $\sigma_s^{\max}$ are the threshold values of the stress state corresponding to initiation of damage process described by parameter $d(\lambda)$ for the uniaxial case (Fig. 8.7) or $d(\lambda_n, \lambda_t, \lambda_\tau)$ in the general 3-D case:

$$d(\lambda_n, \lambda_t, \lambda_\tau) = \sqrt{(\lambda_n)^2 + (\lambda_t)^2 + (\lambda_\tau)^2}. \quad (8.5)$$

The failure criterion in the most general case is formulated as a power law and depends on the fracture energy in the three considered modes: normal $n = I$ and two tangential: $t = II$, $s = III$:

$$\left(\frac{G_I}{G_{Ic}}\right)^2 + \left(\frac{G_{II}}{G_{IIc}}\right)^2 + \left(\frac{G_{III}}{G_{IIIc}}\right)^2 = 1 \quad (8.6)$$

where G_{Ic} , G_{IIc} , G_{IIIc} are the critical values of the fracture energies (CFE). In case of lack of all the above values of CFE estimated experimentally, one can assume that $G_{IIc} = G_{IIIc} = G_{Ic}$, i.e. the failure of the cohesive layer is isotropic.

8.1.3 Simulation Results

Simulations, depending on the type of applied load (force F or moment M), as in Fig. 8.1, were performed separately for tension and bending. However, stretching of samples with asymmetrically deposited TBC layers results in occurrence of additional bending stresses that can cause disproportions of 28–48 % in stresses in extreme layers.

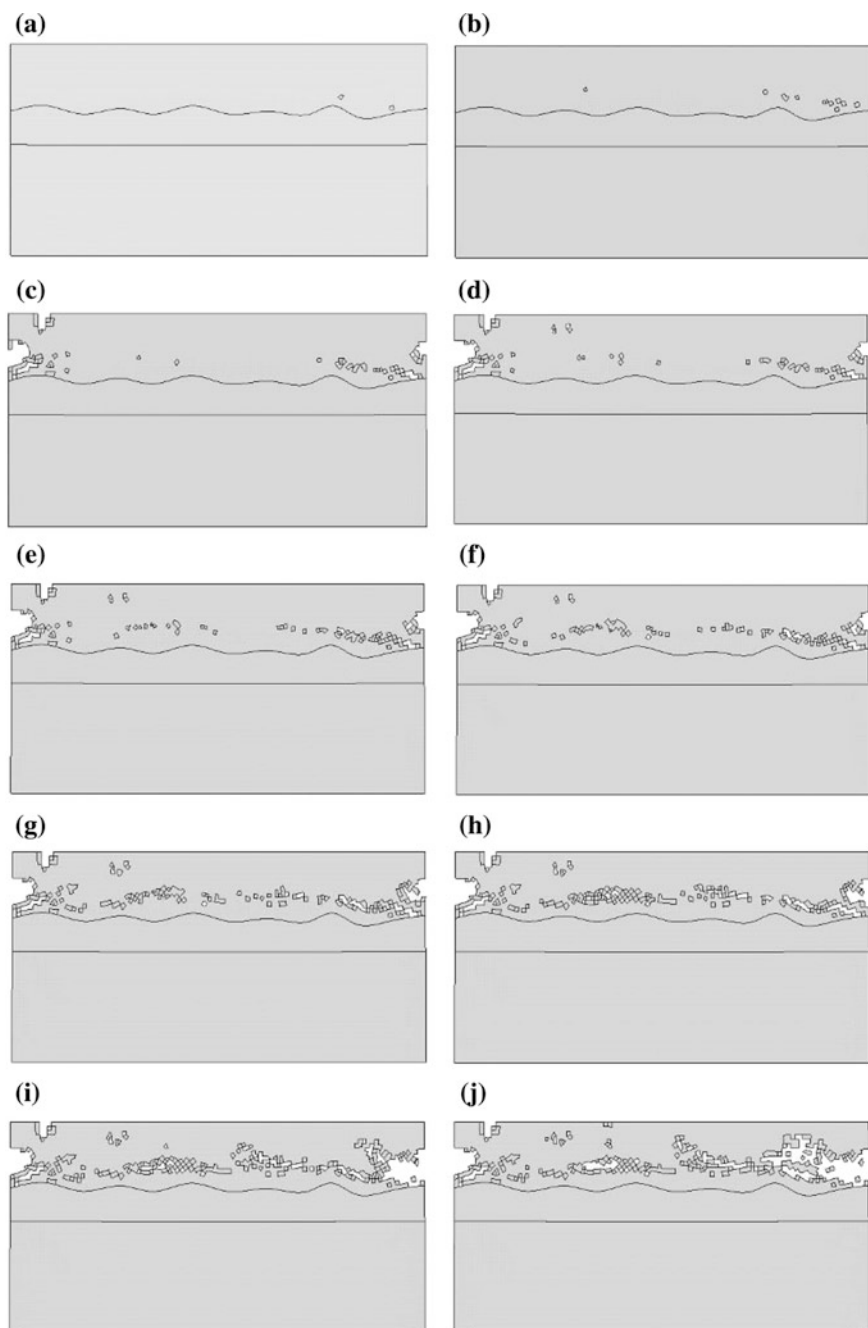


Fig. 8.8 Stages of degradation development in a protective coating during tension

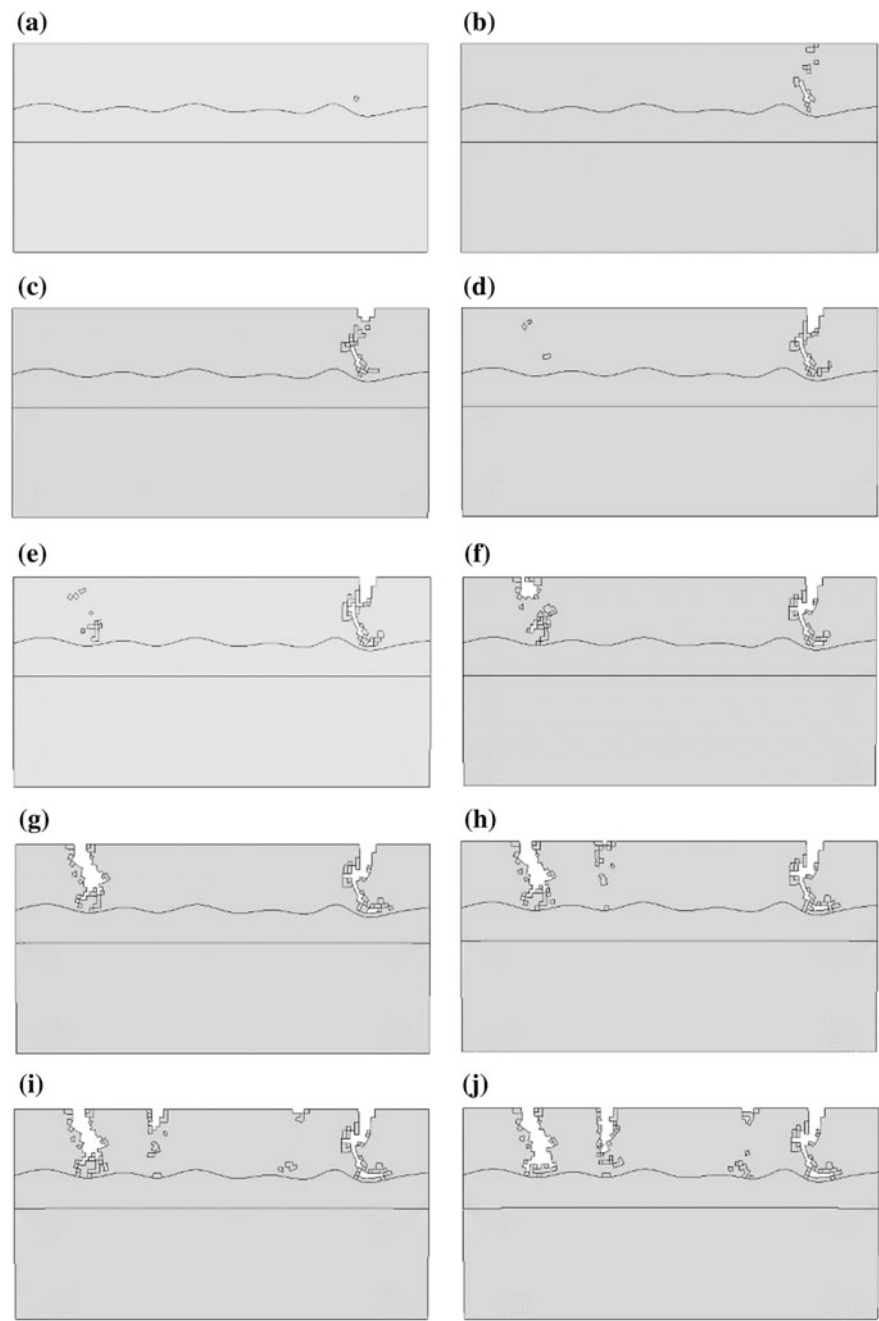


Fig. 8.9 Stages of degradation development in a protective coating during bending

Figure 8.8 presents numerical results for tension process. When analysing simulation results, it must be noted that within the range of loads applied to the samples, destruction evolution is consistent with microscopic (SEM) observations. Damage propagates in the vicinity of the TC–BC boundary, but does not propagate towards the surface or through the boundary inside the BC. Furthermore, the greatest damage occurs at the model's ends, as it was in SEM observations.

An exactly identical damage mechanism can be observed in analysis of samples subjected to bending simulation (Fig. 8.9). In this case, vertical cracks appear that do not cross the boundary into the BC, but only change their direction and propagate along the TC–BC interface.

The proposed method of modelling TBCs can serve for calibrating material data or even as a submodel for simulations that include actual blade geometry.

8.2 Application of Submodeling Technique and X-FEM Methods for Detailed Analysis of Cracking Process in Turbine Blades TBCs

In order to take into account all factors that TBC cracking depends on, such as body forces, thermal loads and alterable geometry, it is necessary to perform numerical tests of a fragment of the turbine blade at the microscopic scale. Below, the use of submodeling and Extended Finite Element Method (X-FEM) for detailed analysis of the selected blade fragment is presented.

8.2.1 Submodeling

The submodeling technique is used for obtaining more detailed and accurate results for the analysed fragment (submodel) of the global model. This technique involves drawing information for the submodel from the global model, which has a thin mesh, as displacement boundary conditions—temperature or stress fields. The submodel has a much denser mesh in comparison to the global model, and consequently the results are more comparable to reality in selected fragments of the analysed model. This technique therefore enables saving calculation time, particularly in situations when simulation results are needed only for a selected place of a relatively large model.

Doubtless, an advantage of this method is the possibility of obtaining a relatively accurate problem solution when a detailed examination of the behaviour of a small area, properly described in a different scale than the large object, is interesting and important. Not without importance are also the savings in time and computing power that would have to be employed when constructing a single model that took into account all details included in submodels.

8.2.2 X-FEM Method Basics

Modelling motionless discontinuities, such as cracks, using the conventional FEM requires the mesh to be consistent with geometry of discontinuities. It is also necessary to increase the mesh density at the crack tip. Modelling crack propagation is even more troublesome, as it requires constant mesh updating, in accordance with the developing crack's geometry.

The X-FEM alleviates the above inconveniences. It was first introduced in [1, 2]. It is an extension of the conventional FEM, based on the 'partition of unity FEM' concept, [3], which enables local enriched functions to be included into approximations of a non-continuous displacement field of a finite element. The presence of discontinuities is ensured by special enriched functions combined with additional virtual degrees of freedom.

For the purposes of fracture analysis, an enrichment function typically comprises functions asymptotic to the crack tip (capturing singularities around it) and a non-continuous function representing the displacement jump of the entire crack surface. Selected nodes around the crack have extra degrees of freedom associated with the enriched function. The approximation takes the form of an extrinsic enrichment of the displacement function u is defined by the following relation:

$$u = \sum_{I=1}^N N_I(x) \left[u_I + H(x)a_I + \sum_{\alpha=1}^4 F_{\alpha}(x)b_I^{\alpha} \right], \quad (8.7)$$

where:

$N_I(x)$ basic shape function for nodes,

u_I node displacement vector for the basic shape function,

$H(x)$ Heaviside jump function,

a_I vector introducing additional degrees of freedom (discontinuity jump),

$F_{\alpha}(x)$ enrichment function asymptotic to the crack tip,

b_I^{α} vector introducing additional degrees of freedom (crack tip).

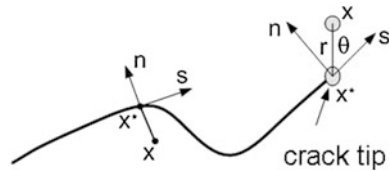
The first expression on the equation's right side applies to all nodes in the model. The second expression is important for nodes crossing the crack. The third expression is only used for nodes located at the crack tip.

The enrichment function $F_{\alpha}(x)$ of crack tips is expressed as:

$$[F_{\alpha}(x), \alpha = 1 - 4] = \left[\sqrt{r} \sin \frac{\theta}{2}, \sqrt{r} \cos \frac{\theta}{2}, \sqrt{r} \sin \theta \sin \frac{\theta}{2}, \sqrt{r} \sin \theta \cos \frac{\theta}{2} \right] \quad (8.8)$$

where r, θ —are the polar coordinates of the coordinate system at the crack tip, Fig. 8.10.

Fig. 8.10 Coordinate system at the crack tip



Cracks initiation and growth criteria, defined as a cohesive degradation of an enriched finite element, can be expressed as:

- function of the principal stress or strains,
- function of the nominal stress or strains,
- coupled criterion in quadratic form (or higher order) related to the state of stress or strains.

8.2.3 Preparation of Model for Simulation

The use of X-FEM and submodeling models will be demonstrated using the description of the cracking process of an engine working blade. It is therefore a continuation of the author's own tests commenced in Chap. 4 where a method of determining stresses in blades was presented and results were verified analytically.

Works discussed in this chapter involved isolating of a small volume fragment from the blade model, where the greatest stress concentrations occurred (Fig. 8.11a). The global model is that the blade, as well as the submodel, must be placed in the same coordinate system. After copying the model, in order to perform the cutting operation by pulling, in order to leave a small volume (submodel), as in Fig. 8.11b, the surfaces created previously were used. The submodel was subsequently divided into partitions and consequently a 0.3 mm-thick TBC protective layer was isolated. It was assumed in the numerical model that the TBC is made of brittle ceramics that is subjected to damage. In the description of this material, the scalar damage parameter d was made dependent on the maximum stress criterion.

The submodel's load comprised the results obtained in the global model simulation, presented in Chap. 4. In order to create a mesh, 104,987 C3D8R linear hexahedral elements were used (Fig. 8.11c). After calculating the submodel, the same displacement values at nodes were obtained, which proves that the procedure was conducted correctly.

At the next stage, a series of simulations were performed for various rotational speeds of the engine, observing the development of damage that appeared and propagated in the TBC layer.

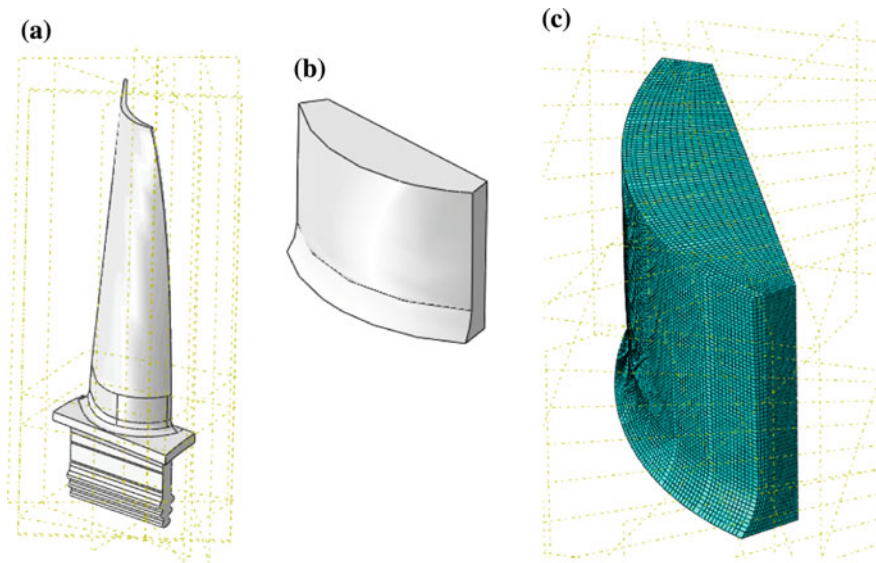


Fig. 8.11 Global engine blade model (a); selected submodel (b); MES mesh of the submodel (c)

8.3 Analysis of Results

As a result of using the X-FEM technique, the acceptable rotational speed for the rotor with embedded blades, at which blade damage does not occur, can be determined.

In the discussed case, the load was pressure from the exhaust gases (constant for all cases) and the rotational speed. The effect was therefore the observation of the effects of rotational speed increase on the damage level in the TBC ceramic layer. The threshold value was 26,750 RPM. Above, within merely 750 RPM, a rapid increase in the number of damaged elements (Fig. 8.12) occurs and consequently— increase in crack length.

The X-FEM method enables observing crack development in engine blades with increasing rotational speed, right up to the critical moment preceding blade defragmentation of the TBC. Gradual development of the crack in an isolated TBC layer of the submodel, as a result of increasing speed, is presented in Fig. 8.13.

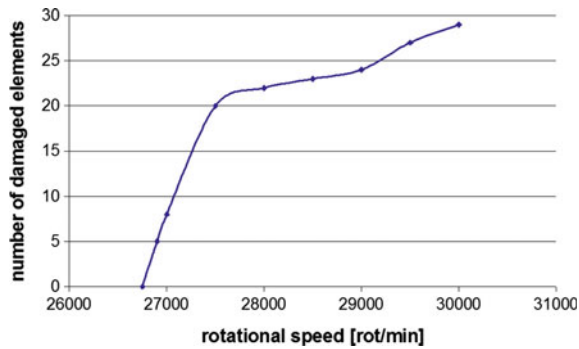


Fig. 8.12 TBC damage development in an engine blade described by the number of removed elements

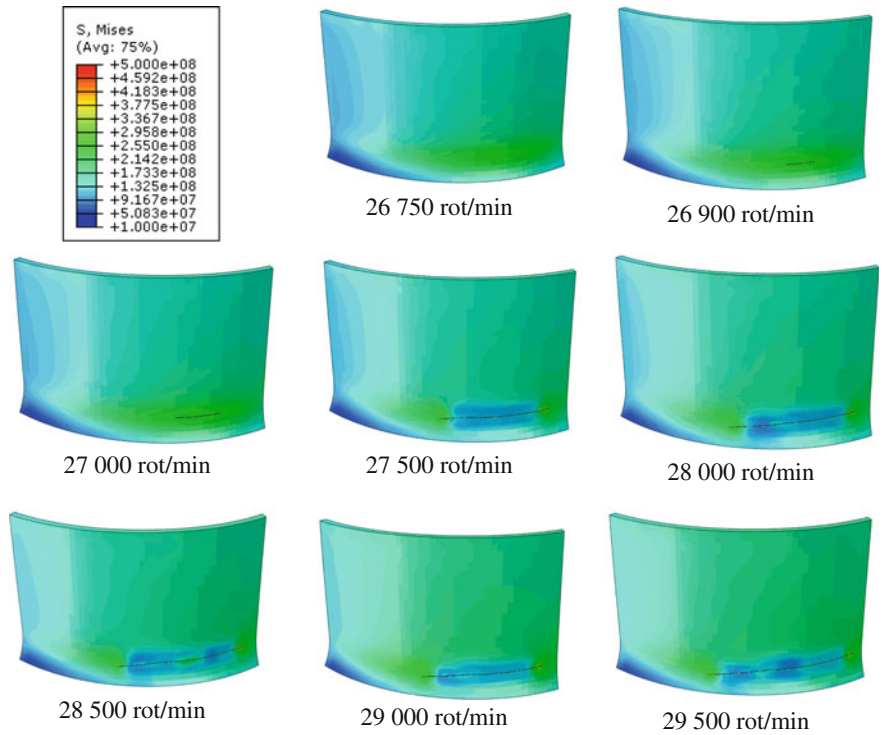


Fig. 8.13 Crack development in a TBC layer as a result of increasing rotational speed of the blade

8.4 Conclusions

The submodeling technique employed in the numerical calculations enabled a more accurate execution of the finite element mesh with a protective TBC layer applied. The section for the isolated fragment, in the global model, was composed of 772 elements, while the submodel was made of 104,987 elements. As a result, more accurate distributions of the Huber—von Mises reduced stress values were obtained, higher by 18.6 % (considering the maximum value) than in the global model. Using the X-FEM technique, the blade's critical rotational speed value, at which the TBC layer is not damaged, was determined. After exceeding the 26,750 RPM speed, quick development of a crack, i.e. removal of elements from the model occurred, up to the speed of 27,500, above which the increase is not as rapid anymore. The presented pattern of solving problems of detecting the most stressed places can be useful when designing blades, so that conducting expensive tests can be avoided.

References

1. Belytschko T, Black T (1999) Elastic crack growth in finite elements with minimal remeshing. *Int J Numer Meth Eng* 45:601–620
2. Belytschko T, Gracie R, Ventura G (2009) A review of extended/generalized finite element methods for material modeling. *Modell Simul Mater Sci Eng* 17(4)
3. Melenk JM, Babuska I (1996) The partition of unity finite element method: basic theory and applications. *Comput Methods Appl Mech Eng* 139:289–314

Chapter 9

Summary

In the book, the use of a new method of assessing damage developing in TBCs, subjected to thermal and mechanical loads, was presented. The method includes both numerical modelling and experimental tests.

A numerical method of determining TBC damage at uniaxial tension, 3-PB and complex states occurring in turbine engine blades was proposed.

In particular, the study's scope covered the following problems of experimental tests and numerical calculations:

I. within the scope of *experimental tests*, the following have been performed:

- optical microscope examinations, including thickness measurement of individual layers of the TBC system,
- working blade surface analyses after a completed service life, in order to determine the content of elements,
- microhardness measurements in order to determine the TBC layer's Young's modulus,
- ageing of dumbbell samples for stretching, and beam samples for bending, for various time intervals and a temperature of 1000 °C,
- uniaxial tension tests of dumbbell samples using the ARAMIS system for measurements of TBC layer damage and acoustic emissions (AE) for the purposes of damage initiation analysis,
- SEM observations in order to determine the TBC damage resulting from stretching, and determine the TGO layer thickness,
- EDS X-ray analyses in order to determine the content of elements in individual layers after ageing,
- 3-PB tests, in a holder designed by the author, enabling adjustment of supports and the use of AE for determining damage initiation,
- microscopic observations for samples subjected to bending.

II. within the scope of *numerical tests*, the following have been performed:

- FEM model of the steering blade with an internal cooling channel, and thermal-flow calculations in order to determine the temperature distribution in the blade and the TBC,
- proper vibration frequency calculations for the working blade, with a TBC and without a coating, for various rotational speeds within the 0–30,000 RPM range, and for the temperature range of 0–900 °C,
- calculations of stress and temperature distributions in an FGM coating and a two-layer coating, subjected to thermal loads,
- calculations of thermal loads for individual stages of protective coating deposition,
- calculations of bending-induced stresses in a dumbbell bone sample subjected to UTT tests,
- analysis of the effects of testing machine holder shape during shearing tests on the value of force that causes delamination of the protective coating,
- FEM model of the TBC structure, including damage, and simulations for tension and bending,
- FEM model with the use of the advanced X-FEM technique and submodelling for determining the critical rotational speed value of a blade with TBC. The primary scientific goal of the study was the analysis of operation of blade and

The conducted numerical and experimental tests allowed for the following conclusions:

- currently, there is no clear answer to what material containing rare earth elements can be used as a replacement for YSZ to increase blade operation temperature and increase engine power,
- the use of ceramic coatings results in decreasing the proper vibration frequency throughout the considered speed range, in comparison to a coatless blade. For the first form, these differences range from 4.7 to 7.4 % and increase with increasing rotational speed,
- one of the elements detected on the working blade's surface was chlorine, and it can facilitate the occurrence of chemical corrosion and, together with the forming surface cavities, can reduce its fatigue resistance,
- in terms of assessing initiation of the TBC layer damage during uniaxial tension tests, a more effective method than the ARAMIS system appears to be AE,
- EDS measurements, after ageing, indicate diffusion of elements between all layers,
- an important factor when using TBCs are internal stresses occurring as a result of deposition onto the metallic substrate. Stresses in the coating are from 7 to 27 times higher for cases when the blade is not heated. Pre-heating should therefore be applied, as the ceramic layer may be damaged during deposition,
- for non-aged samples and set deflection of 0.8 mm, no visible edge cracks were observed during 3-PB tests. However, delamination at the interface of TC and

BC layers occurs at the sample's edge. By extending the ageing process, various phases of damage development at the same set displacement can be observed,

- when analysing simulation results for TBC stretching, it must be noted that within the range of loads applied to the second batch of samples subjected to ageing process, destruction evolution in a model is consistent with microscopic observations,
- as a result of using the X-FEM technique and submodelling, the acceptable rotational speed for the rotor with embedded blades, at which blade damage does not occur, can be determined,

Further works will be aimed towards new experimental tests and numerical simulations that should reflect as best as possible the loads that protective coatings are subjected to during operation. It significantly influence proper design of the turbine blades of jet engines covered by the TBCs systems.