Influence of the Bond Coat Roughness on Life Time of APS Thermal Barrier Coating Systems under Thermo-Mechanical Load

A. Schmidt, A. Scholz, T. S. Mao and C. Berger [a], W. Stamm [b]

[a] Institute of Materials Technology, Darmstadt University of Technology, Grafenstr. 2, D-64283 Darmstadt, Germany

[b] Siemens Power Generation, Mellinghofer Str. 55, D-45473 Mülheim an der Ruhr

* Corresponding author. Tel.: +49 6151 162451, fax: +49 6151 165659, E-mail address: scholz@mpa-ifw.tu-darmstadt.de

Abstract

The influence of the bond coat roughness on the life time of air plasma-sprayed (APS) thermal barrier coating systems (TBCs) was investigated under thermo-mechanical (TMF) load. The TBC system was applied on hollow cylindrical specimens made of the single crystal super alloy CMSX-4 in the orientation <001> with a MCrAlY-bond coat. Two different values of the bond coat roughness were investigated.

In order to study the influence of the thicknesses of the thermally grown oxide layer (TGO), the specimens were isothermally oxidised at 1000 °C for a long term prior to the TMF experiments.

The thermo-mechanical experiments show a higher number of cycles-to-failure for TBCs corresponding to an increase of the bond coat roughness. Furthermore, it could be demonstrated that a certain TGO thickness is needed to produce a total delamination of the top coat in the TMF experiments. This minimum thickness varies with the surface roughness of the bond coat and the TMF cycle's phase shift and strain range.

Crack initiation and crack growth were investigated by microscopical analyses, for example, SEM and EDX. Therefore most of the experiments were completed before a total delamination of the top coat occured. On the basis of these investigations, crack initiation and crack growth under thermo-mechanical load were described systematically and a failure map was developed.

Keywords: thermal barrier coating system, air plasma sprayed, bond coat roughness, thermo-mechanical fatigue, crack initiation, crack growth

1. Introduction

The efficiency factor of gas turbines can be increased either by process technical parameters like the pressure ratio or the temperature increase of the hot gas [1-3]. The temperature of the hot gas is limited by the maximum bearable temperature of the hot gas components. Because of their high mechanical, thermal and partial chemical (corrosive) load turbine blades are critical components. Advanced Nickel-based alloys with a high γ'–fraction (Ni_3 (Al, Ti)) are standard materials for modern gas turbine blades. Today the most critical components are made of single crystal super alloys [4, 5]. In order to increase the temperature of the hot gas over the super alloy's limit, turbine blades are air-cooled in the first stages.

The temperature of the hot gas can be increased even further by the application of thermal barrier coating systems (TBCs). Ceramic top coats with low thermal conductivity are applied together with an efficient cooling of the turbine blades. Because of the increase of the gas turbine's efficiency factor and the reduction of the environmental impact, there is a large interest in thermal barrier coating systems as a design element for gas turbines. This would enable the TBC to operate reliably without component failure over an inspection interval of 20,000 to 30,000 hours, in the case of industrial gas turbines.

It is essential to increase the knowledge about the damage evolution of thermal barrier coating systems under thermo-mechanical loading [6, 7]. The influence of the bond coat's surface roughness on the evolution of delamination cracks is of special interest [8].

The aim of this project was to determine, which surface roughness leads to a longer life time of plasma-sprayed thermal barrier coating systems under thermo-mechanical loading. Further more, crack initiation and crack growth are described and compared with theoretical considerations. Additional experiments with EB PVD coatings have been performed on insular specimens, but are not described in this paper.

2. Material and specimen preparation

In order to obtain a geometry resembling the leading edge of a turbine blade, a thin-walled hollow specimen was designed (Fig. 1). The specimens were machined from hollow bars out of the single crystal super alloy CMSX-4 (cristallografic orientation <001>) and coated by low pressure plasma spraying (LPPS) with a metallic (MCrAlY) bond coat. The 8% Yttrium (Y_2O_3) partially stabilised Zirconia (ZrO_2) ceramic top coat was deposited by means of air plasma spraying (APS). The bond coat's average surface roughness (R_a) was measured according to ISO 11562, prior to the top coat application. The bond coat roughness was varied by the particle size of the spraying powder. Therefore, average values of the surface rougness of 7 and 10µm were established.

In order to reduce the amount of time that single specimens spend in the TMF test rig, the specimens were isothermally oxidised at 1000 °C in air, prior to the TMF experiments. The specimens were oxidised between 300 and 6000 h to establish values of the TGO-thickness between 3 and 10 µm (Table 1) [6].

3. Equipment and test conditions

The experiments were performed in TMF-cycles corresponding to the load of an industrial and an aero gas turbine respectively (Fig. 2). In the case of the industrial gas turbine-cycle the influence of the strain range (0.6% and 0.3%), the TGO-thickness (3, 7 and 10 µm), the phase shift (In-Phase and Out of Phase) and the bond coat's surface finish were varied, while in the case of the aero gas turbine cycle only the bond coat's surface finish was varied.

Specimen heating was realised with an infrared heating device (Fig. 3), with integrated compressed air cooling. In order to increase the efficiency of the infrared heating, the specimens were coated with a thin layer of iron oxide [3]. The temperature was measured by thermocouples on specifically designed thermocouple mountings at the specimen's shoulders, while a pyrometer acts as a backup system. Experiments were performed on a servo hydraulic testing machine in strain control mode. The specimen's displacement was measured by a dual acting side-contact extensometer. At the contact points of the thermocouples and the extensometer the ceramic coating was cut away since displacement and temperature were measured at the metallic bond coat's surface. In addition a CCD camera was used for online observation of crack initiation in the gauge length. After the TMF-testing, the specimens were investigated by microscopical analyses, SEM and EDX [9].

4. Experimental results

In the case of the industrial gas turbine cycle under out-of-phase load macroscopic delamination cracks in the ceramic top coat occure, when a certain thickness of the TGO layer was established before the TMF experiment. Experiments under out-of-phase load with a TGO thickness less than the minimum value lead to vertical cracks in the bond coat (Fig 4). The number and the size of these vertical cracks are reduced with decreasing mechanical load, here the total strain range of the TMF cycle. Specimens with a TGO-thickness of 8 to 10 µm however show a delamination of the ceramic top coat under out-of-phase load (Fig 5).

Under in-phase loading conditions, a smaller minimum value is observed. An example given in Fig 6 with a TGO thickness of 3 µm leads to the formation of delamination cracks in the ceramic top coat. Therefore in-phase experiments were used to investigate the influence of the bond coat surface roughness on the life time of the TBC. As a result, a higher value of the surface roughness leads to a longer life time (Fig. 7 and 8). In addition, it can be observed that the crack location shifts from the ceramic top coat (Fig. 7) towards the interface TBC/TGO (Fig. 8).

Additional experiments under out-of-phase loading conditions as well as thermo-cyclic experiments confirm the findings above.

Finally, experiments with the aero-gas-turbine cycle show vertical cracks in the bond coat as well as delamination cracks in the ceramic top coat (Fig. 9). These insular results have to be confirmed by future investigations [10].

5. Finite Element Calculations

In order to promote the understanding of the damaging mechanisms and the damage evolution in the TBC under thermo-mechanical load, finite element calculations with the software „ABAQUS" have been carried out. For simplification, the complex surface of the bond coat (Fig. 10) was modelled by a sinusoidal profile (Fig. 11). The growth of the thermally grown oxide before and during the TMF experiments was simulated with the swelling function of ABAQUS. For all components of the TBC system (ceramic-top coat, bond coat, TGO and substrate)

data for viscoplastic material behaviour was used. Material data were partly derived from previous investigations [11] and compiled by the working group, which accompanied the research work.
With this model, the local stresses in specific elements in the peak and valley region of the sinusoidal interface were calculated. It was assumed, that tensile radial stresses, which promote the growth of delamination cracks and compressive radial stresses, inhibit the growth of delamination cracks (mode I crack growth). Further more, it was assumed that the stresses at low temperature were the most critical ones, because of the ductile-to-brittle transition [12].
The analysis of the local stresses leads to radial tensile stresses in the peak region of the sinusoidal interface [8] and compressive stresses in the valley region for out-of-phase loading (Fig. 12) as well as for in-phase loading (Fig. 13). From this, it was concluded that delamination cracks start in the peak region and crack growth is inhibited in the valley region. With increasing TGO-thickness, the stresses change to compressive stresses in the peak region and tensile stresses in the valley region (Fig. 14), thus allowing the cracks to grow through the valley region and link with neighbouring cracks to form a macroscopic delamination. Since the initial compressive stresses in the valley region under in-phase loading (Fig. 13) are lower than those under out-of-phase loading (Fig. 12), a lower TGO-thickness is needed to cause a macroscopical delamination under in-phase-loading.
A higher amplitude of the sine wave, representing a higher surface roughness leads to higher compressive stresses in the valley region. Thus a higher TGO-thickness is needed to cause a macroscopic delamination.

6. Discussion

The influence of the thickness of the TGO-layer on the failure of TBC systems due to local growth stresses is well known in the literature [13-17]. Further more, due to shielding effects, a higher surface roughness leads to a greater TGO-thickness that is needed in order to introduce a delamination of the ceramic top coat. This observation contributes to a concept of a critical TGO-thickness for the delamination of the ceramic top coat [15, 16]. Finite element calculations show for low values of TGO-thickness that both out-of-phase as well as in-phase TMF loading cause tensile stresses in the peak regions of the bond coat and compressive stresses in the valley region of the bond coat (Fig. 14a) [14]. Microstructure observations show crack initiation in the TGO of the peak region. This is confirmed by investigations in [9]. The stress state changes with increasing TGO thickness [14] and leads to compressive stresses in the peak region and tensile stresses in the valley region (Fig. 14b). Further, these observations show that the crack path changed from the TGO into the ceramic top coat. Because of the tensile stresses the cracks can link together and form a macroscopic delamination of the ceramic top coat (Fig. 14c).
Further more the finite element analysis of the local stresses shows that in-phase loading promotes the formation of delamination cracks, while out-of-phase loading decelerates the formation of delamination crack. Pure thermal cycling lies between in-phase and out-of-phase load [8]. In [18, 19] it is assumed that compressive stresses at low temperature are needed to cause a delamination of the ceramic top coat. The analysis of the global stresses during the experiments (e.g. the measured force related to the cross section in the gauge length) shows that an in-phase load leads to compressive stresses at low temperature while an out-of-phase load causes tensile stresses at low temperatures. Therefore, from the analysis of the global stresses it can be concluded that an in-phase loading promotes the delamination of the ceramic top coat. Since a greater TGO thickness leads to a faster delamination of the ceramic top coat, it can be assumed that the growth stresses contribute to an increase of the stresses followed by delamination.
On the basis of these results, a failure map showing typical damage configurations for different types of TMF and TF loading was developed [8]. This failure map can be of valuable help for maintenance and service tasks.
As a result of the experiments with plasma-sprayed (APS) top coats, a minimum thickness of the TGO-layer that is needed for the delamination of the top coat could be defined (Table 2). This minimum TGO-thickness depends on the surface roughness and the loading cycle. Since the values in Table 2 are based on the experimental experiences in this work they are limited to the TMF cycles and TBC coating systems that were used here. Nonetheless the results show that the loading conditions as well as the surface roughness of the bond coat have to be put into consideration, if a critical TGO-thickness is defined. Residual stresses were not put into consideration but will be in future works.
In order to describe damage of TBC systems additional 4-point-bendig experiments have been performed parallel on pre-oxidised specimens limited to 2000 h pre-oxidation time [20]. As a result, no influence of surface roughness on energy release rate was found. But, long term pre-oxidised specimens are planned for future investigations.

7. Conclusions

In this work, the life time of different TBC, and bond coat systems under thermo-mechanical loading conditions were evaluated. The effects of the thermal aging (TGO-thickness), the top-coating/bond-coating interface roughness and the cycle type on the number of cycles-to-failure were investigated with the following conclusions:

- A certain TGO-thickness is needed to cause a delamination of the TBC. This minimum TGO-thickness varies with the bond coat's surface roughness and the loading conditions (In-Phase, Out-of-Phase, dwell time at high temperatures, total strain range, etc.).
- APS TBCs with a bond coat's average surface finish of 10 µm leads to a higher number of cycles-to-failure in comparison to a lower value of 7 µm.
- These experimental observations could be verified by finite element analysis.
- Typical damage configurations for different types of TMF and TF loading were summarised in a failure map.
- Crack initiation and crack propagation were explained with the help of finite element analysis and microstructure investigations.

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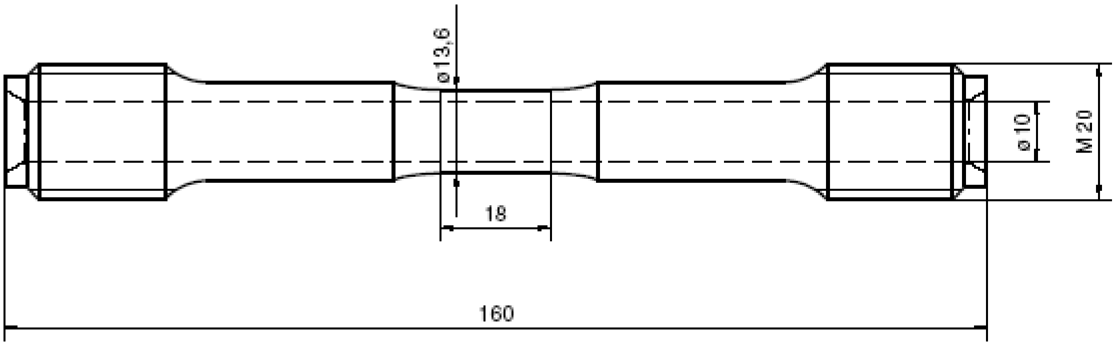
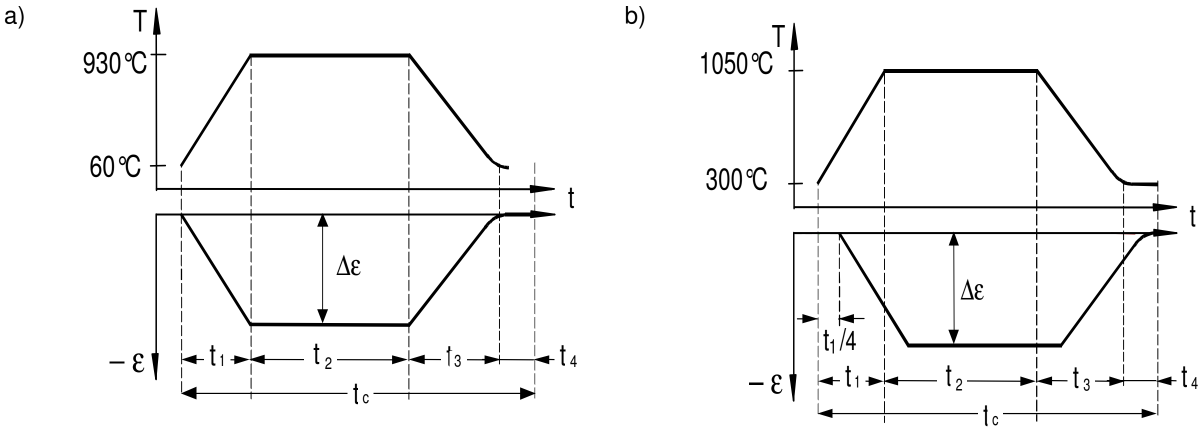


Figure1: Specimen for the thermo-mechanical (TMF) experiments



a)

t_1 min	t_2 min	t_3 min	t_4 min	t_c min	Δε %
4	8	4	4	20	0/0.3/0.6

b)

t_1 min	t_2 min	t_3 min	t_4 min	t_c min	Δε %
2	2	2	2	10	0.3

Figure 2: TMF-cycles, industrial gas turbine cycle and aero gas turbine cycle, cycle period t_c.

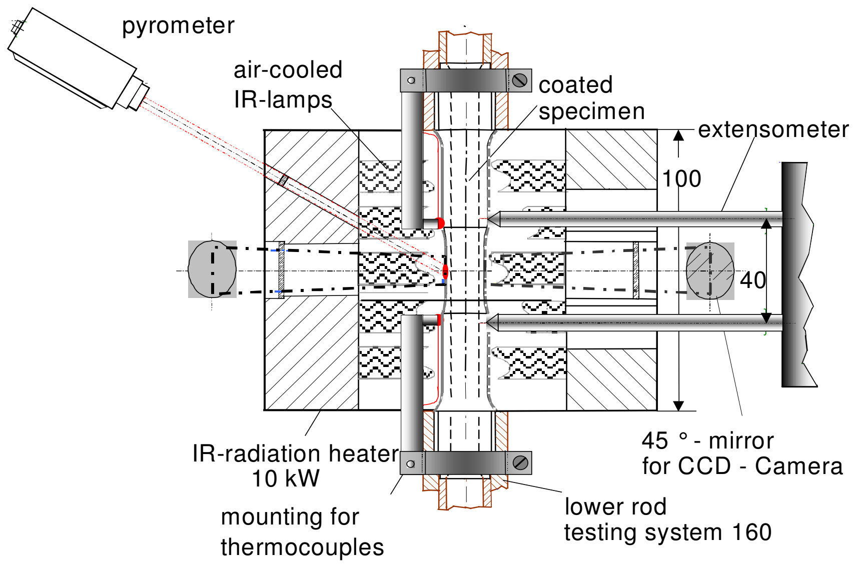


Figure 3: Schematic image of the experimental set-up (front view).

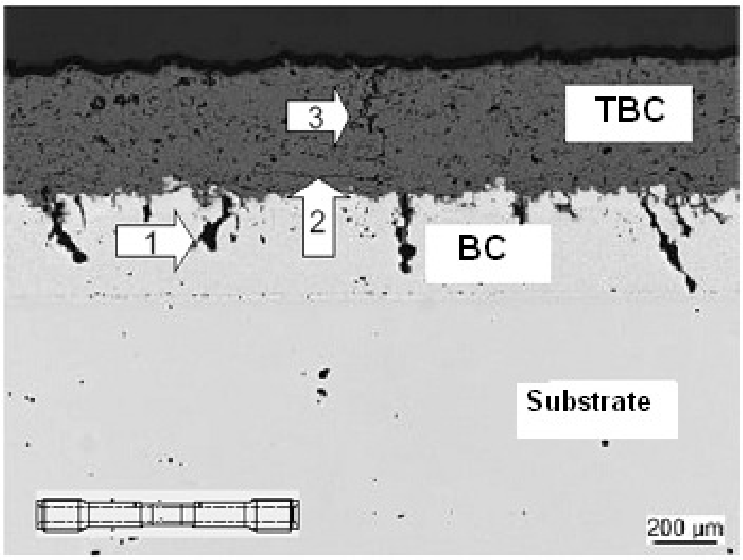


Figure 4: APS TBC specimen with a CoNiCrAlY bond coat, average surface finish of $\mathbf{R_a = 10\ \mu m}$**,** 1000 TMF cycles in the industrial gas turbine cycle under **out-of-phase loading** ($\Delta\varepsilon = 0.6$ %, TGO-thickness **3 µm**), (1) vertical cracks in the bond coat, (2) segmentation crack in the TBC, (3) small delamination crack in the TBC.

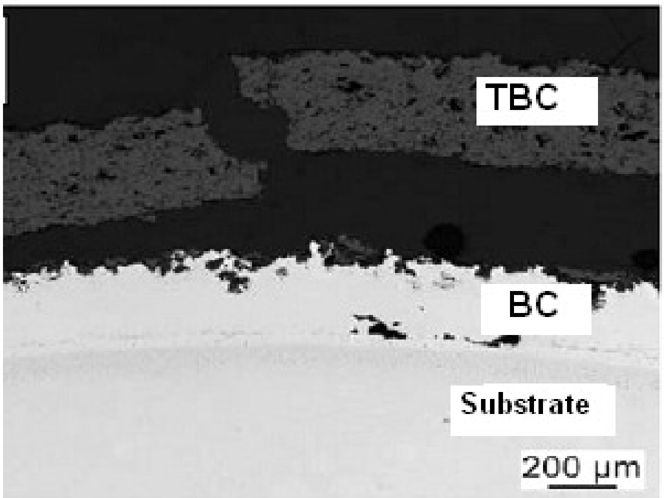


Figure 5: APS TBC specimen with a CoNiCrAlY bond coat, average surface finish of $\mathbf{R_a = 10\ \mu m}$**,** 1000 TMF cycles in the industrial gas turbine cycle under **out-of-phase loading** ($\mathbf{\Delta\varepsilon = 0.6\ \%}$, TGO-thickness **8-10 µm**), total delamination of the TBC.

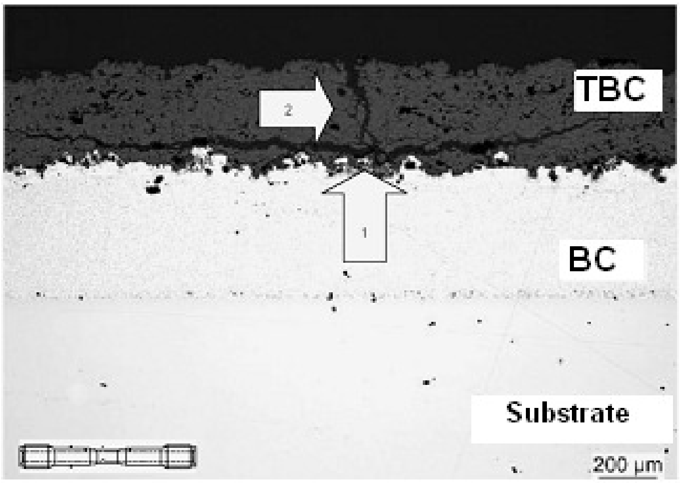


Figure 6: APS TBC specimen with a NiCoCrAlY bond coat, average surface finish of $\mathbf{R_a = 10\ \mu m}$**,** 1400 TMF cycles in the industrial gas turbine cycle under **in-phase load** ($\mathbf{\Delta\varepsilon = 0.3\ \%}$, TGO-thickness **3 µm**), (1) delamination crack in the TBC, (2) segmentation crack in the TBC.

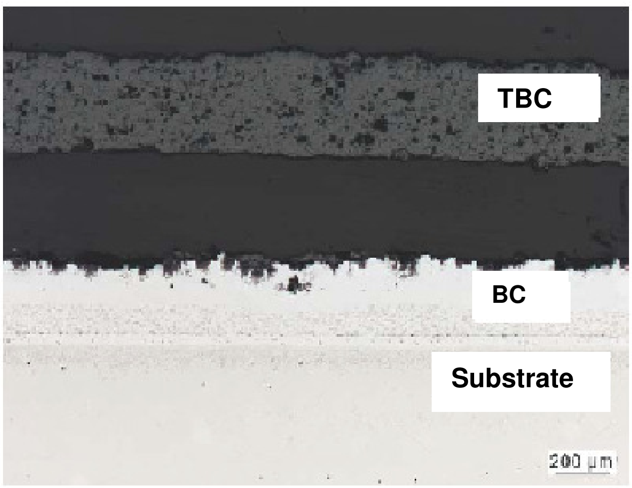


Figure 7: APS TBC specimen with a CoNiCrAlY bond coat, average surface finish of $\mathbf{R_a = 7\ \mu m}$**,** 300 TMF cycles in the industrial gas turbine cycle under **in-phase loading** ($\mathbf{\Delta\varepsilon = 0.3\ \%}$, TGO-thickness **8-10 µm**).

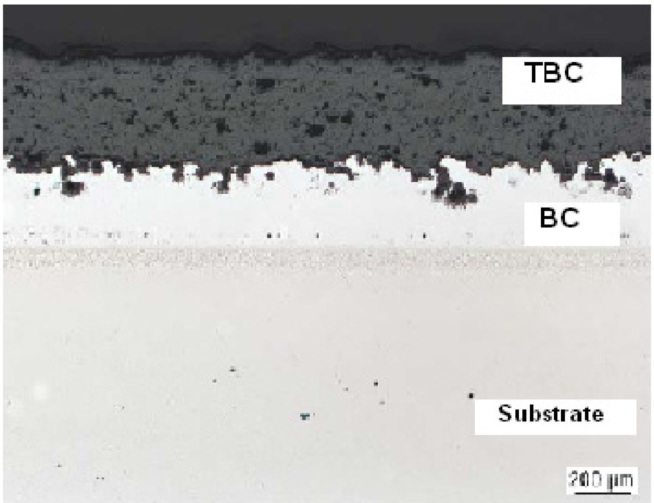


Figure 8: APS TBC specimen with a CoNiCrAlY bond coat, average surface finish of $\mathbf{R_a}$ **= 10 µm**, 600 TMF cycles in the industrial gas turbine cycle under **in-phase load** (**$\Delta\varepsilon$ = 0.3 %**, TGO-thickness **8-10 µm**).

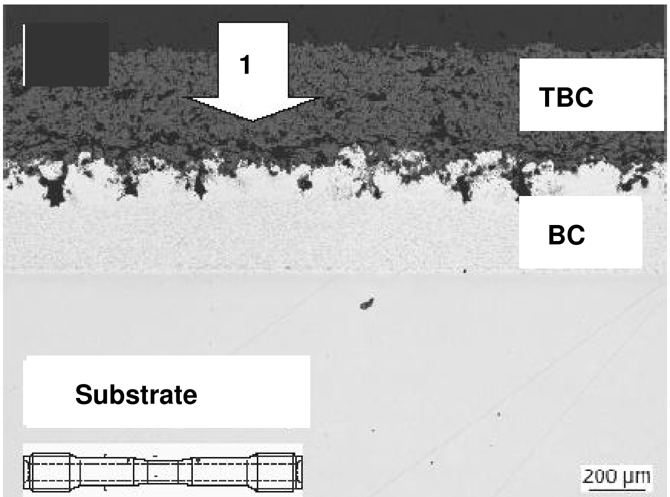


Figure 9: APS TBC specimen with a CoNiCrAlY bond coat, average surface finish of R_a = 10 µm, 2445 TMF cycles in the **aero gas turbine cycle** (**$\Delta\varepsilon$ = 0.3 %**, TGO-thickness 3 µm).

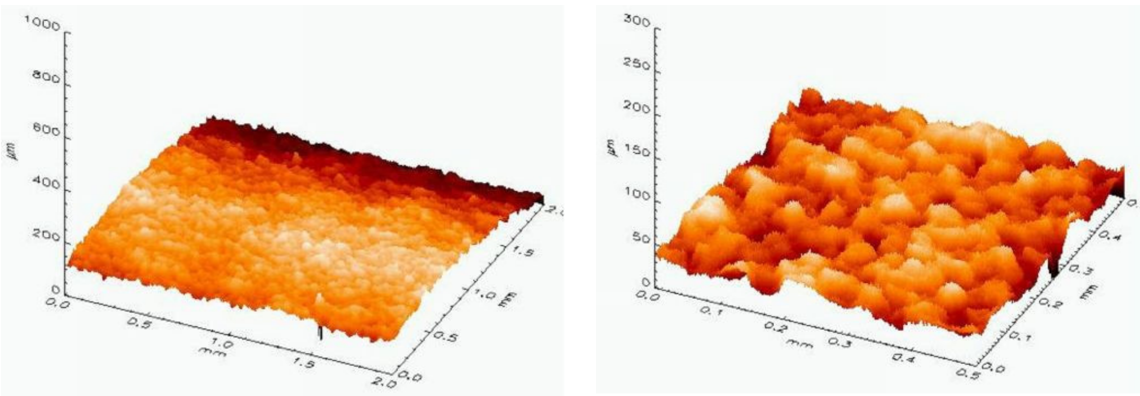


Figure 10: Real surface of the CoNiCrAlY bond coat on a TMF specimen (measured with 3D topography).

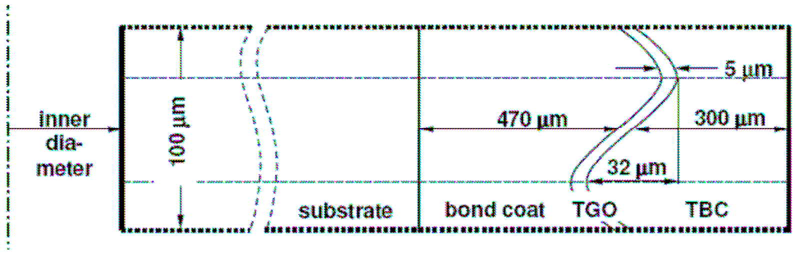


Figure 11. Finite element model of the TBC-system with sinusoidal bond coat surface.

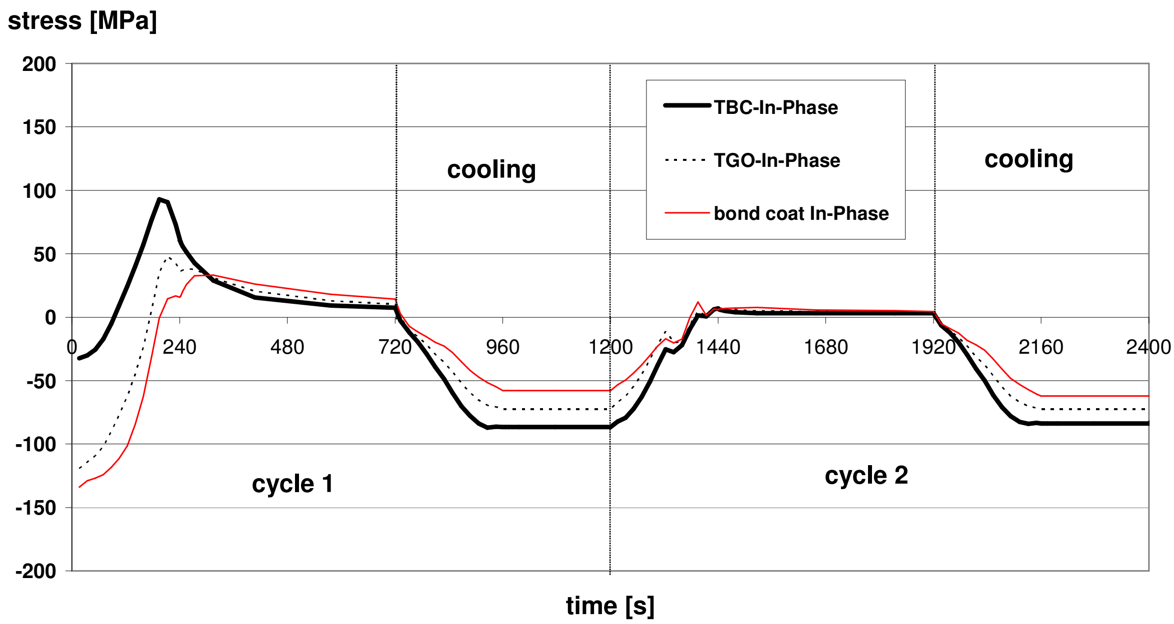


Figure 12: Local radial stresses in the **valley region** of the sinusoidal bond coat surface under **In-Phase** loading.

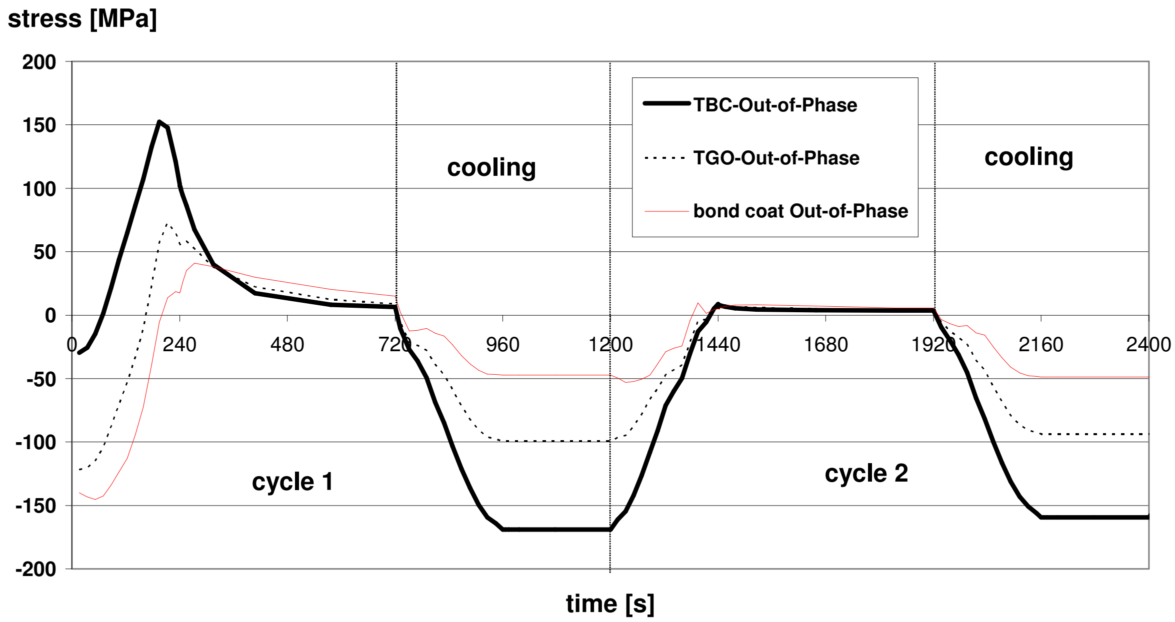
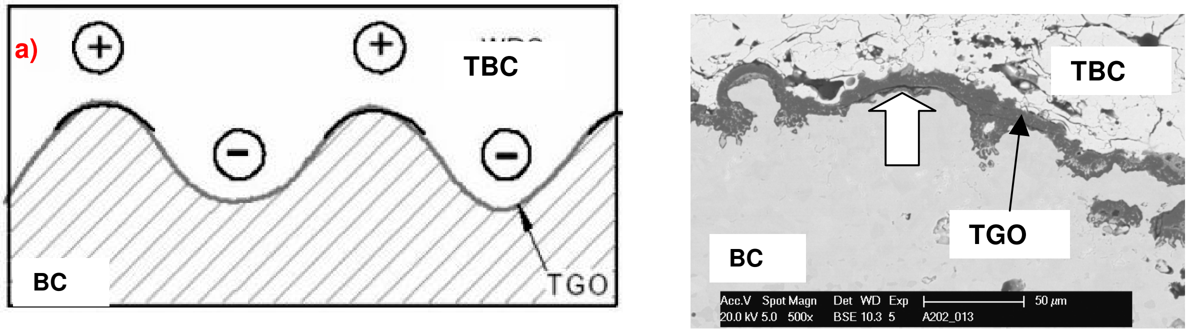
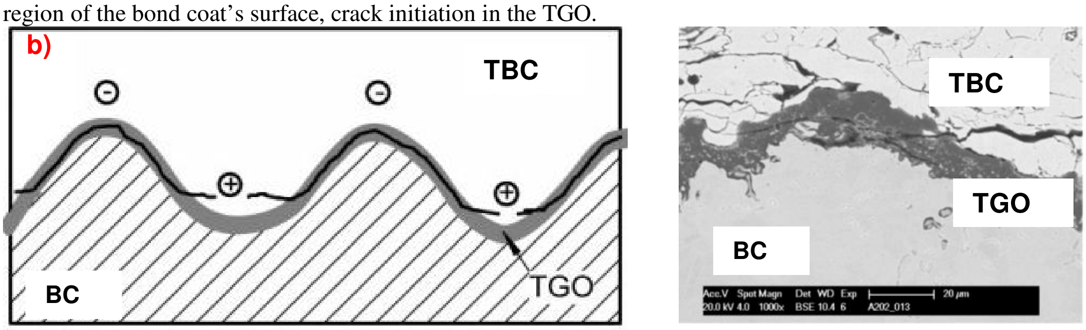


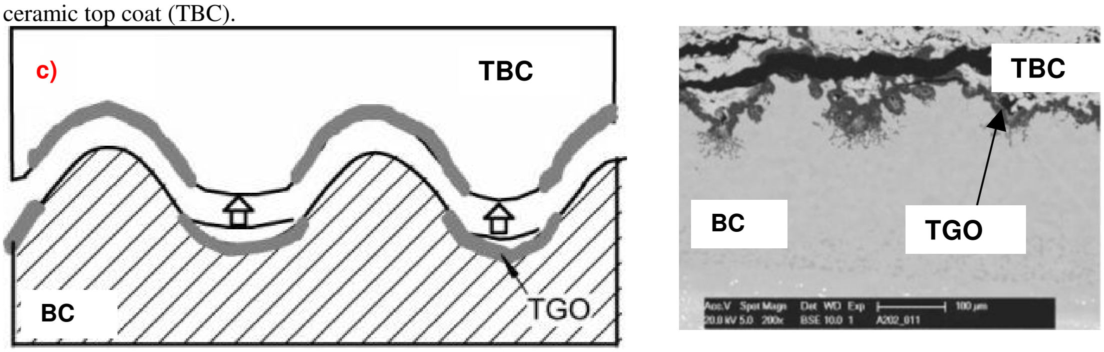
Figure 13: Local radial stresses in the **valley region** of the sinusoidal bond coat surface under **Out-of-Phase** loading.



a) Initial stress state in the TBC system. Tensile stresses (+) in the peak region and compressive stresses (-) in the valley region of the bond coat's surface, crack initiation in the TGO.



b) Change of the stress state in the TBC system due to TGO growth stresses. Compressive stresses (-) in the peak region and tensile stresses (+) in the valley region of the bond coat's surface. The crack path changes from the TGO to the ceramic top coat (TBC).



c) The cracks link together and form a macroscopical delamination.
Figure 14: Change of the stress state with increasing TGO-thickness.

CoNiCrAlY bond coat surface roughness [µm]	**time at 1000 °C isothermal pre-oxidation [h]**	**TGO-thickness [µm]**	**number of specimens**
7	200	3	3
7	2000	7	3
7	6200	8-10	1
10	200	3	3
10	2000	7	4
10	6200	8-10	2

Table 1: List of APS TBC specimens.

	surface roughness [µm]	
	7	**10**
loading	**TGO-thickness [µm]**	
In-Phase	3	4
Out-of-Phase	8	11
Thermal Fatigue	7	10

Table 2: Minimum values of TGO-thickness for a delamination of the ceramic top coat.