Evaluating deformation behavior of a TBC-System during thermal gradient mechanical fatigue by means of high energy X-ray diffraction

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Evaluating deformation behavior of a TBC-system during thermal gradient mechanical fatigue by means of high energy X-ray diffraction

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Outline

1. Realistic thermomechanical testing with thermal gradients

2. Interpreting experimental results by means of numerical models

3. Model validation by means of in situ strain measurements via high energy X-ray diffraction at Argonne APS*

*APS=Advanced Photon Source
Stress distribution due to thermal gradient

- Hot outer wall
- Cooled inner wall
- Biaxial compressive stress
- Biaxial tensile stress
- Cooling air
Investigated coating system

- **Columnar TBC**
  - $\text{ZrO}_2 + (6-8) \text{wt.-\\% Y}_2\text{O}_3$
  - $\alpha = 10 \cdot 10^{-6} \text{K}^{-1}$

- **TGO**
  - $\text{Al}_2\text{O}_3$
  - $\alpha = 8 \cdot 10^{-6} \text{K}^{-1}$

- **Bond Coat**
  - MCrAlY, PtAl
  - $\alpha = 14 - 16 \cdot 10^{-6} \text{K}^{-1}$

- **Substrate**
  - Nickel-base superalloy

- Near surface:
  - 1 - 10 $\mu$m
  - ~30 - 100 $\mu$m

- Near TGO:
  - 120 - 200 $\mu$m

- Image of columnar structure with scale bars for 20 $\mu$m.
Test facility for thermal gradient mechanical fatigue

16 Quartz lamps, 1 kW each

Internally cooled tensile test specimen

Thermal Gradient Mechanical Fatigue = TGMF
View of open furnace
Summarizing thermal and mechanical loads

- Maximal material temperatures ca. 1000°-1100°C
- Thermal gradient (temperature drop over a ceramic TBC of 100-200µm thickness of about 80°-150°C)
  - High thermal heat flux
  - Multiaxial thermally induced stresses
- High thermal transients (heating and cooling rates)
- Superposed mechanical loads (centrifugal forces on rotating blades)
Thermal mechanical load cycle – representing the fatigue load of flight cycle

- It is not practical to perform test cycles with realistic cycle duration (e.g. 2 - 10 hour flights) - thus: reduced dwell times
- But: time at high temperature has major impact on lifetime of the coating

Considering time dependent effects by pre-ageing

<table>
<thead>
<tr>
<th>Time at 1000°C</th>
<th>TGMF-cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 h</td>
<td>500 (25h)</td>
</tr>
<tr>
<td>250 h</td>
<td>1000 (50h)</td>
</tr>
<tr>
<td>500 h</td>
<td>until spallation</td>
</tr>
</tbody>
</table>

Pre-ageing + Thermomechanical fatigue
Failure after thermomechanical laboratory testing

after 933 TGMF-cycles & 500h pre-ageing at 1000°C
3-dimensional sketch of defects

Summary of experimental results

• Without pre-ageing no spallation up to 7000 cycles

• 250h (500h) pre-ageing + 1000 cycles, open delamination cracks, spallation

- Evolution of the 'smiley' cracks is linked to cracks in the TGO, perpendicular to the applied mechanical load.
- Initial TGO cracks are generated due to axial tensile stresses
- The questions are

  - How can axial tensile stresses evolve in the TGO during TGMF tests?
  - Why do they only evolve in pre-aged specimens?
After pre-ageing: bi-layer thermally grown oxide

200h/1000°C

Fine grained intermixed zone
$\text{Al}_2\text{O}_3 + \text{ZrO}_2$

Coarse grained
$\text{Al}_2\text{O}_3$
Numerical model: Geometry and boundary conditions

Bi-layered TGO

M. Hernandez, A.M. Karlsson, M. Bartsch: Surface Coatings & Technology 203, 3549-58, 2009
Stress free at homogenous temperature of 1000°C

Electron Beam - Physical Vapor Deposition (EB-PVD)

⇒ high residual stresses at ambient temperature
Numerical model: load cycle

- Temperature at the outer surface is shown
- Thermal gradient: time-dependent temperature difference between outer and inner wall (not shown)
- Mechanical cycle TGMF

Highest mechanical tensile load, thermal gradient near stationary conditions
Axial stresses for elastic – plastic material properties

Stress free at $T_{\text{processing}}$ (1000°C, homogenous)

Axial stresses across the specimen wall due to
- thermal gradient
- mechanical load
- property mismatch

TGO always under compression
even at highest mechanical tensile load

Surface temperature: 1000°C

M. Hernandez, A.M. Karlsson, M. Bartsch: Surface Coatings & Technology 203, 3549-58, 2009
Including time dependent TGO properties: growth strain and creep / relaxation

Thickening $\varepsilon_t$ and lengthening $\varepsilon_l$ growth strain

\[ \varepsilon_l = 0.1 \cdot \varepsilon_t \]

Growth strain increases the compressive stress in TGO!

Relaxation decreases the compressive stress in TGO!


Effect of TGO properties on stress accumulation

Mech. Load
Temperature

1000°C
RT

time

External wall
Inner wall

Deformation of TGO
Linear-elastic
+ TGO-growth

Deformation of TGO
Effect of TGO properties on stress accumulation

Mech. Load

Temperature

1000°C

RT

Deformation of TGO

Deformation of TGO

External wall

Inner wall

fast relaxation

slow relaxation
Evolution of axial TGO-stresses

Hypothesis: Initiation of fatigue crack in TGO due to accumulation of tensile stress during subsequent TGMF-cycles
Open questions – and a method to get answers

• Mechanical material properties of the coating materials are still unknown: Temperature dependent elastic properties, yield strength, creep laws of TGO (intermixed zone and coarse grained layer), bond coat and TBC

• Strategy:
  • measuring the strains in the coating system during TGMF by means of high energy X-ray diffraction
  • calculating (fitting) the respective material properties by means of finite element simulation
Experimental set-up at Argonne Advanced Photon source

- Argonne National Laboratory, Argonne, Illinois
- Synchrotron high energy X-Ray beam-line; 65 keV beam energy
Top view of heater and beam

- 4 focused infrared lamps
  - 8 kW total

- Beam exit window
  - $17^\circ$ 4θ

Servohydraulic testing machine on µm - positioning rig

Assembling heater, grips and specimen at Argonne APS
Measurement method

**Loading parameter:**
- thermal cycle (80 min)
- outer surface temperature max. 1000°C, temperature difference between outer and inner surface ca. 150°C
- variation of thermal gradient by variation of cooling flow rate
- superposition of mechanical load

**Beam parameter:**
- 65 keV beam energy
- exposure time 0.5 to 15 sec.

X-Ray diffraction 2-D strain measurements

- Measure radial position around azimuthal angle
- Calculate each directional strain using \((\text{Ro}-\text{R})/\text{Ro}\)
  - \(\text{R} = \) measured radius
  - \(\text{Ro} = \) strain free radius

K. Knipe, Nature Comm. 5 (2014) article Nr. 4559
YSZ - strain results

- No thermal gradient
- 25°C
- Variation of mechanical load
- X-Ray scan through coating thickness
- Every 3.5 minutes
- Window size 30 x 300 microns
- 10 window scan
Strain measurement during cyclic loading

- Outer surface ramped up to 1000°C in 20 minutes and then held for 40 minutes
- Coolant flow rate for gradient varied
  - 30, 50, and 75 % max. flow (100 SLPM* max)
- Constant nominal mechanical stress
  - 32, 64 and 128 MPa applied

SLPM* = standard liter per minute
Strain in YSZ during thermal cycle

- 64 MPa
- 75% cooling air flow rate

at room temperature:
- compressive in plane strain \( e_{22} \)
- tensile out of plane strain \( e_{11} \)

at high temperature:
- strain reduces (closer to stress free condition at manufacturing temperature)

\[ \begin{align*}
\text{Outer Surface Temperature (deg C)} & \quad \text{YSZ (111) } e_{11} \\
0 & \quad -0.6 \\
20 & \quad -0.8 \\
40 & \quad -1 \\
60 & \quad -1.2 \\
80 & \quad -1.4 \\
100 & \quad -1.6 \\
120 & \quad -1.8 \\
\end{align*} \]

\[ \begin{align*}
\text{Outer Surface Temperature (deg C)} & \quad \text{YSZ (111) } e_{22} \\
0 & \quad -1.8 \\
20 & \quad -1.8 \\
40 & \quad -1.8 \\
60 & \quad -1.8 \\
80 & \quad -1.8 \\
100 & \quad -1.8 \\
120 & \quad -1.8 \\
\end{align*} \]

K. Knipe, Nature Comm. 5 (2014) article Nr. 4559
Strain in bond coat $\beta$-NiAl during thermal cycle

- $64 \text{ MPa}$
- $75\%$ cooling air flow rate

at room temperature:
- tensile in plane strain $e_{22}$
- compressive out of plane strain $e_{11}$

at high temperature:
- strain reduces (stress free at manufacturing temperature)

TGO stress in pre-aged specimen during thermal cycle

Pre-aged specimen: 304h at 1000°C
- the TGO experience tensile stresses under TGMF loading depending on applied mechanical tensile load and thermal gradient.
- Relaxation occurs during dwell time at high temperature, which is a condition for accumulating tensile stress during cycling.
Conclusions and outlook

• In situ strain measuring by X-ray diffraction
  • gives for each load case an equation for determining the respective material properties
  • test results can be used for validating numerical models and adapting laboratory experiments to more realistic conditions, e.g.
    • are dwell times and transients appropriate, e.g. time for relaxation processes within one load cycle appropriate? – example: stress accumulation in TGO
    • effect of time dependent processes captured?– TGO growth? Material property changes?

• Aim: validated realistic laboratory test for turbine blade materials for investigating damage mechanisms and contributing to life time modelling.

• Relevance-check of laboratory test: are observed damage mechanism and failure mode realistic?
Thank you for your attention!

Questions?

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Publications


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