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The influence of heating and cooling rates on TBC failure in high heat flux tests

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Siemens Corporate Technology

Presentation Outline

Introduction

- High heat flux testing is commonly used to assess TBC robustness
- TBC is tested under thermal gradient, similar to engine conditions
- Many test parameters can be varied
  - Surface temperature
  - Metal temperature
  - Number of cycles
  - Hold time during hot plateau
  - …

Which combination of test parameters yields relevant results quickly?

High heat flux testing (HHFT) to assess TBC robustness

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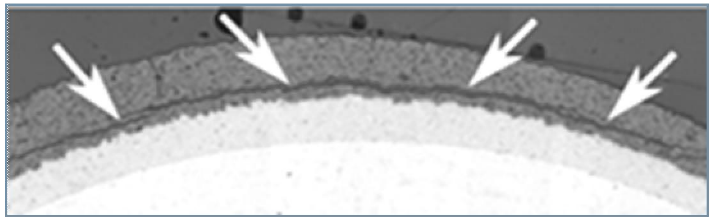
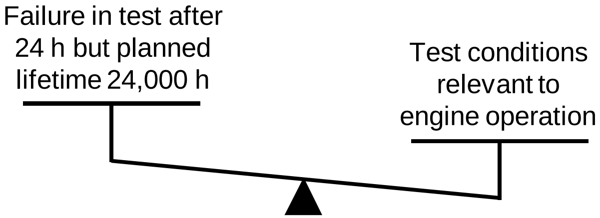
Failure model

- Assess delamination of TBC caused by thermo-mechanical stress under temperature gradient
- Other failure modes are out of scope of HHFT, e.g. erosion



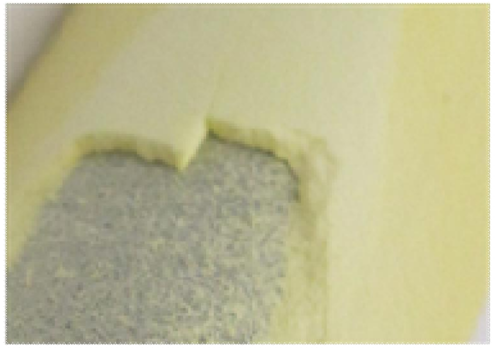
Acceleration for high throughput

- Test conditions must be more aggressive than in the engine to speed up failure
- Test must avoid inappropriate failure mechanisms, e.g. due to excessive surface temperature



Test output

- Rank robustness of different TBC designs
- Compare quality of different TBC batches
- Cannot predict lifetime in engine without field feedback



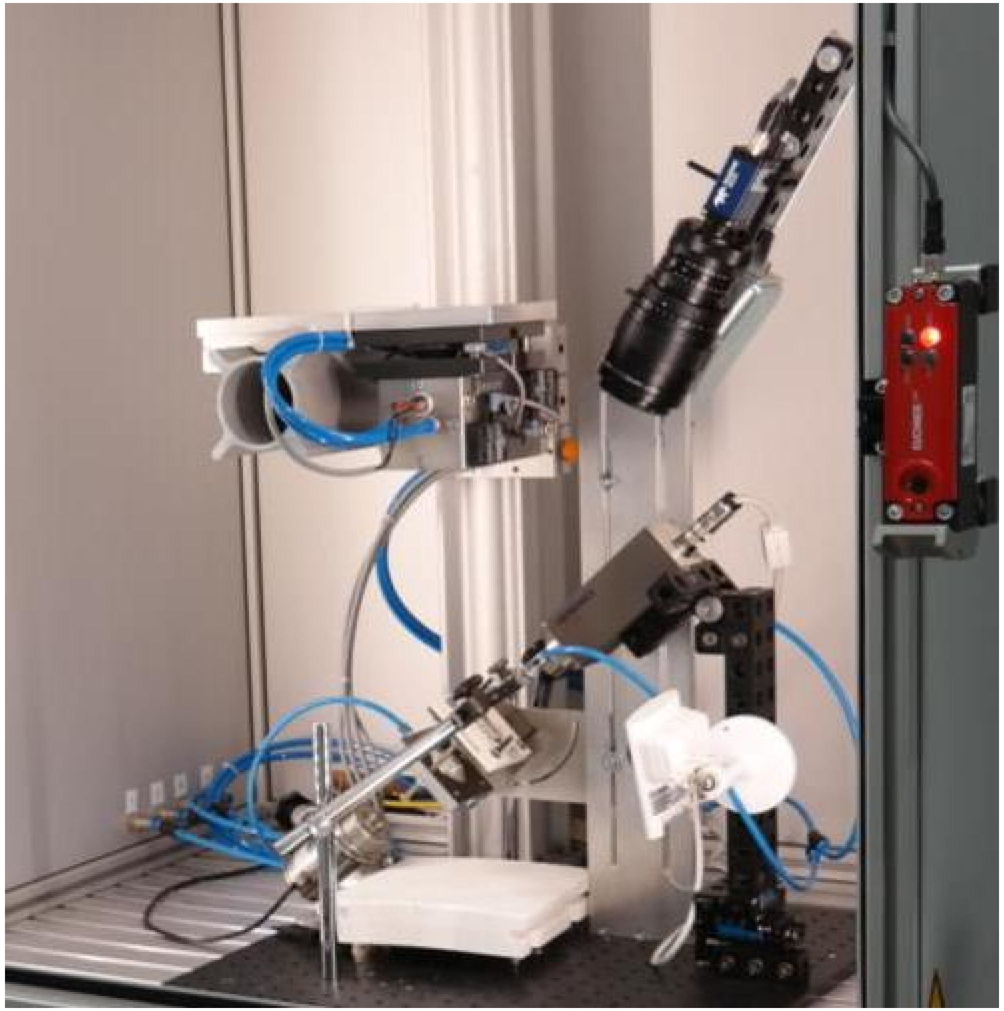
Test conditions for accelerated testing need to be more aggressive than in the engine while still inducing relevant failure mechanism

Presentation Outline

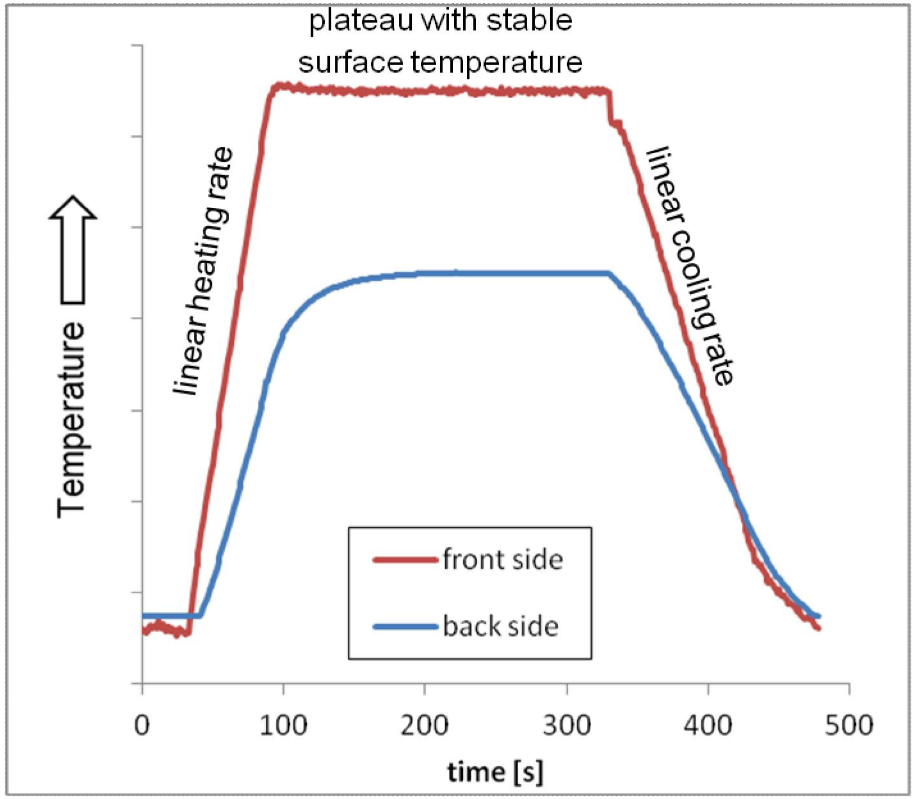
Laser-based rig for high heat flux testing

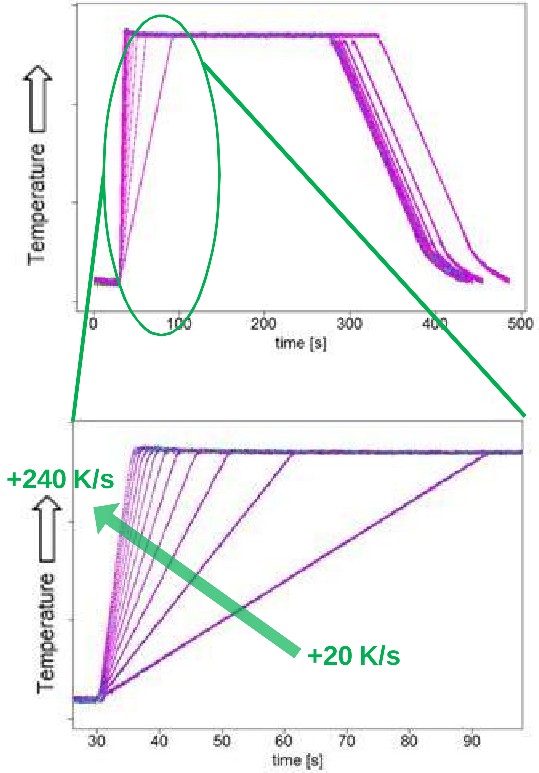
HHFT bench developed at Siemens

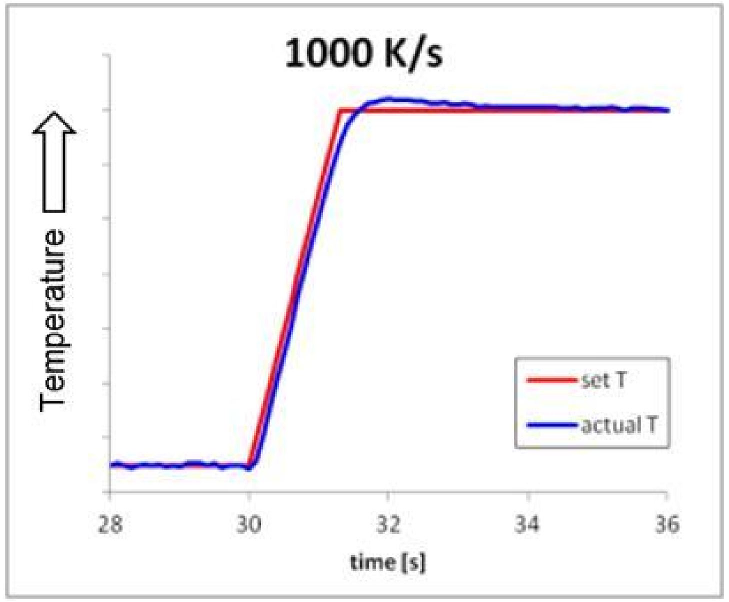
- Accelerated lifetime testing of TBC under thermal gradient
- Generation of realistic stress in TBC
  and hence relevant failure mechanism
- Heating / cooling rate: 0.1 - 2000 K/s
- TBC surface heated with laser: 100 – 1800 °C
- Controllable temperature gradient
- Flexible sample geometry: discs, sub-components, …
- Automated failure detection
- Modular control software



Example temperature cycles in laser HHF test



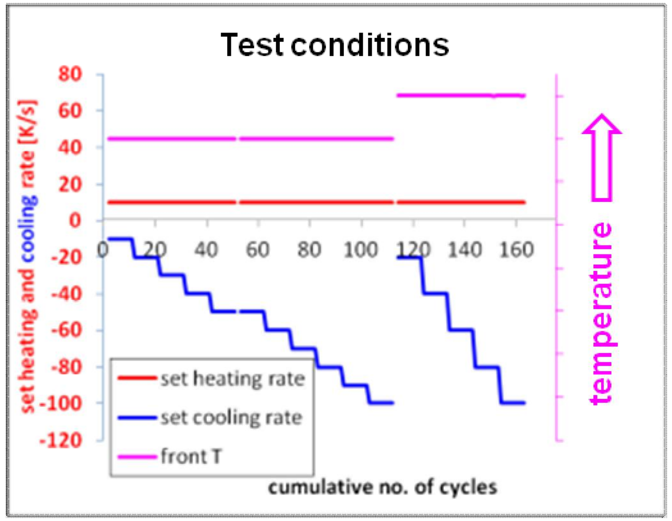


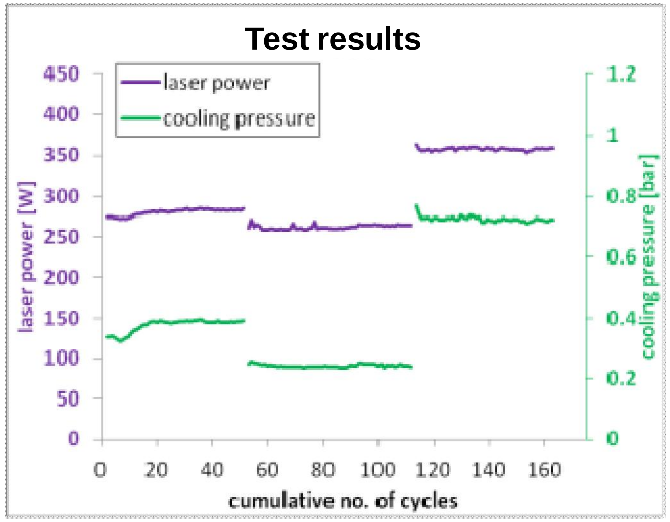


Unlike a burner rig, laser HHFT rig enables precise control of heating and cooling rates

Presentation Outline

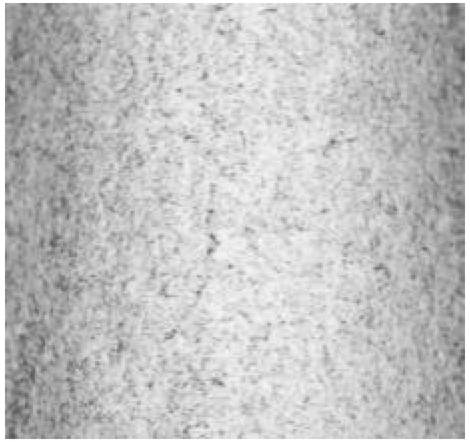
Increasing cooling rate and low heating rate (1)



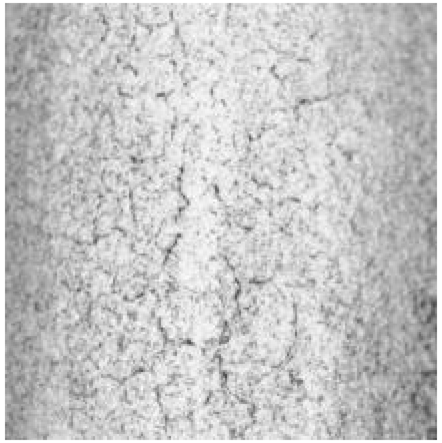


- No indication of delamination
- Development of network of vertical cracks

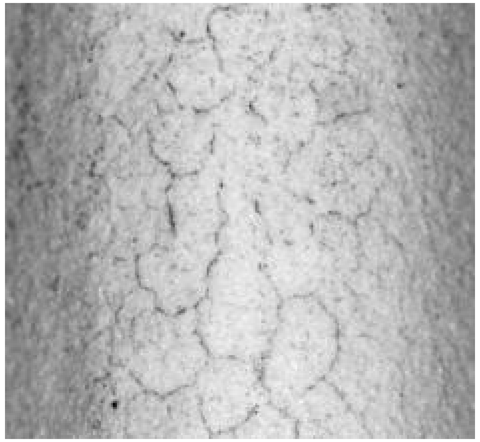
T < 1200 °C, -50 K/s



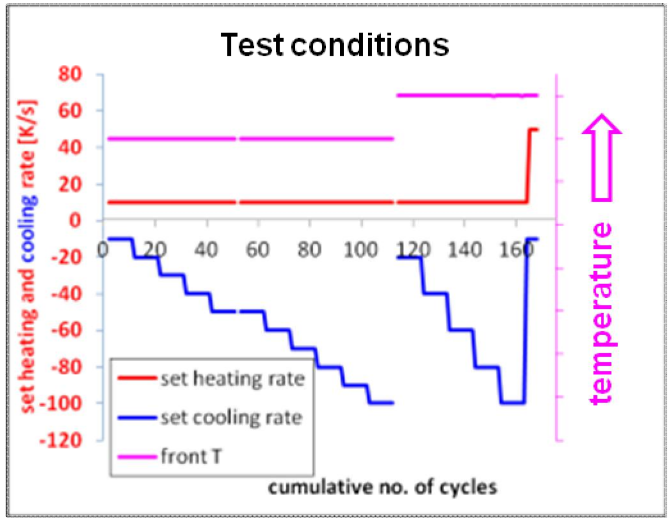
T > 1200°C, -100 K/s

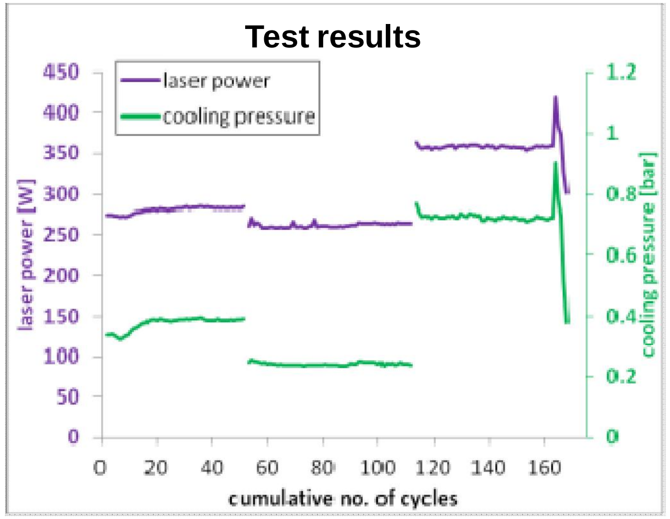


T >> 1200°C, -100 K/s

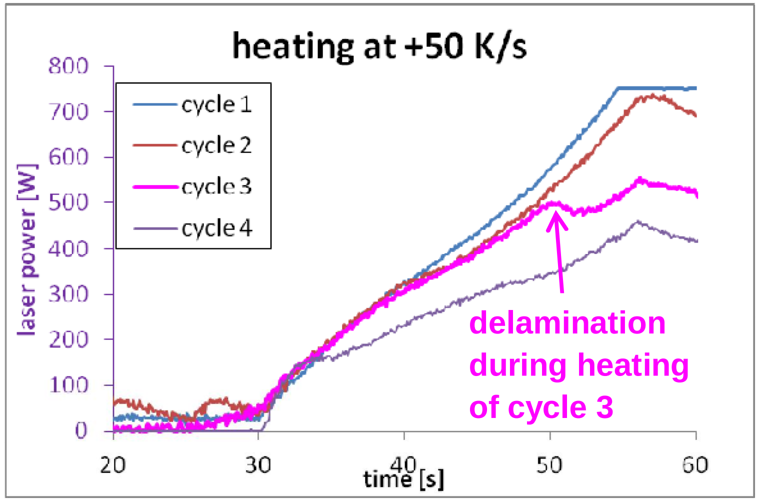


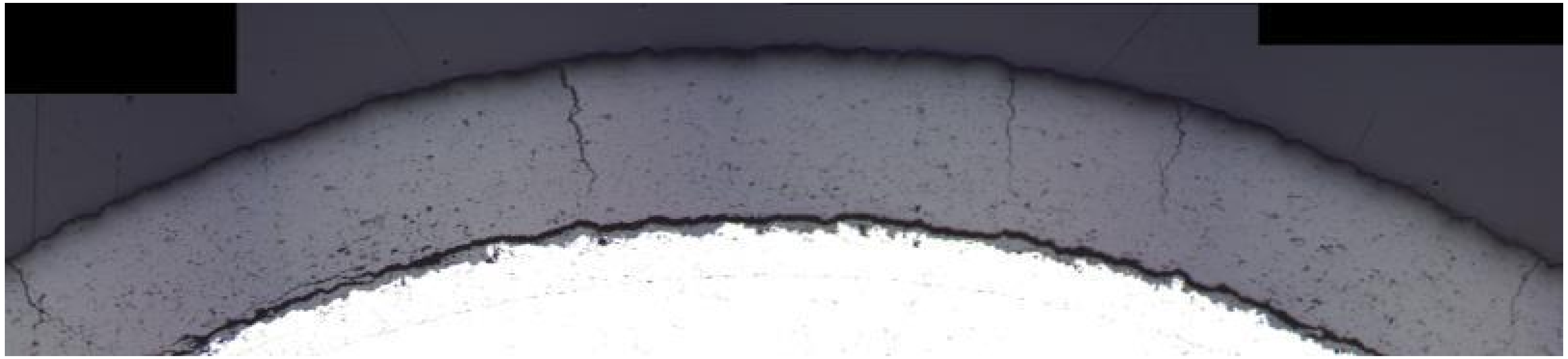
Increasing cooling rate and low heating rate (2)



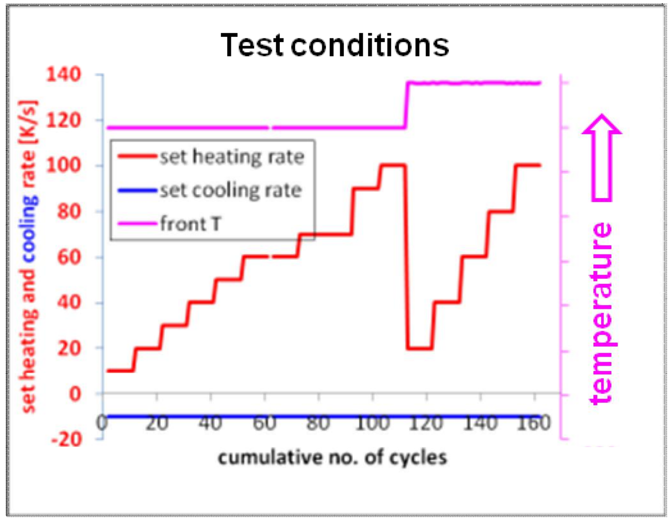


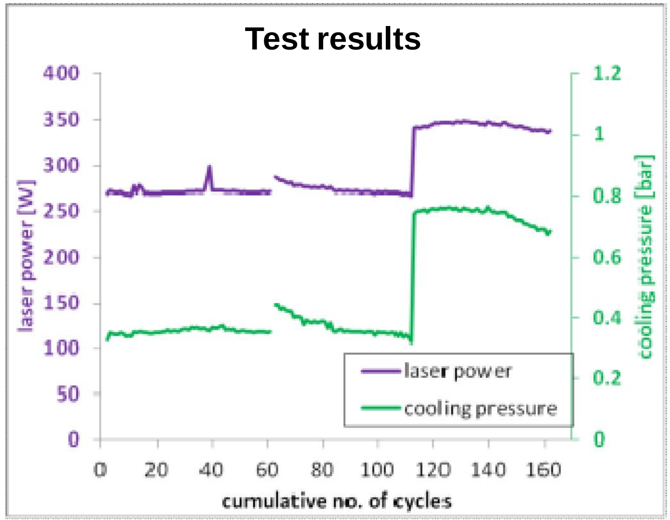
- Reduce cooling rate to -10 K/s
- Increase heating rate from +10 K/s to +50 K/s
- Failure in < 10 cycles
- Delamination confirmed by met





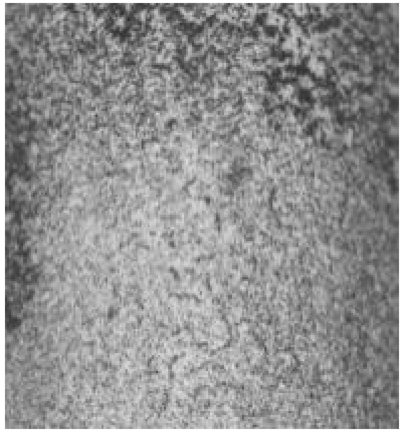
Increasing heating rate and low cooling rate (1)



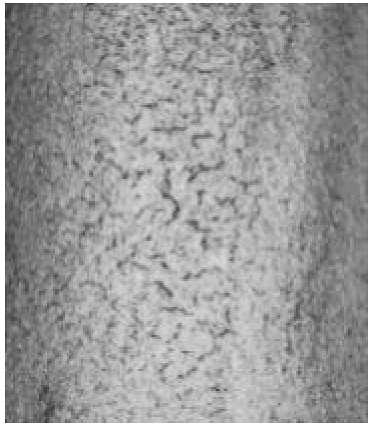


- No indication of delamination
- Gradual development of network of disconnected vertical cracks

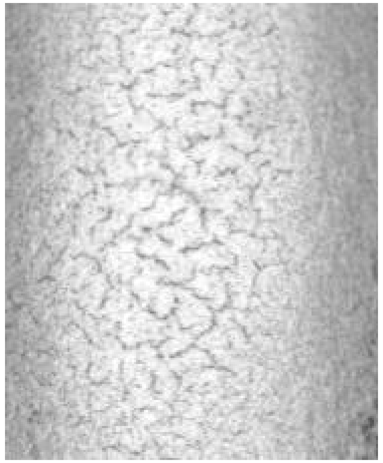
T > 1200°C, +60 K/s



T > 1200°C, +100 K/s



T >> 1200°C, +100 K/s



Increasing heating rate and low cooling rate (2)

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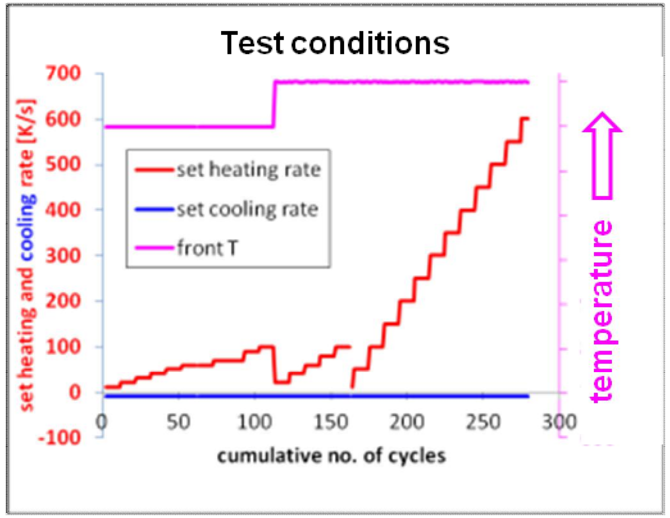
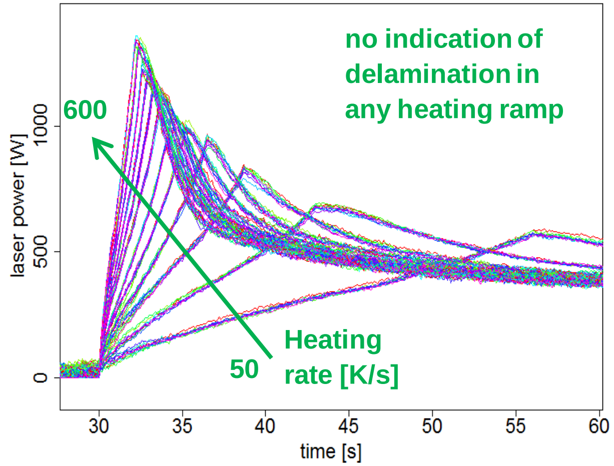
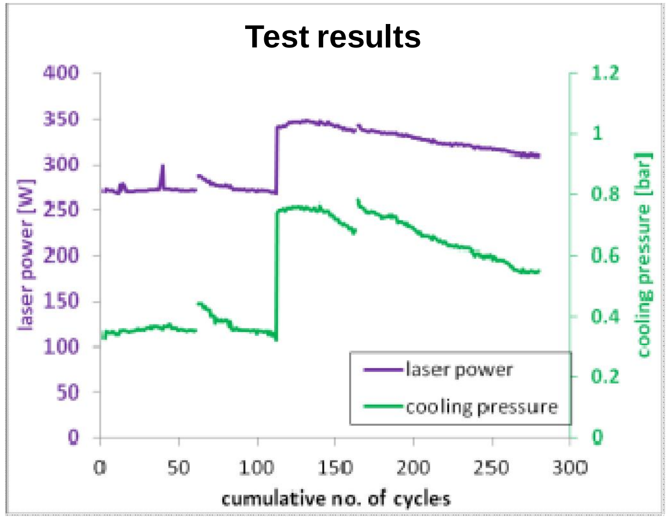
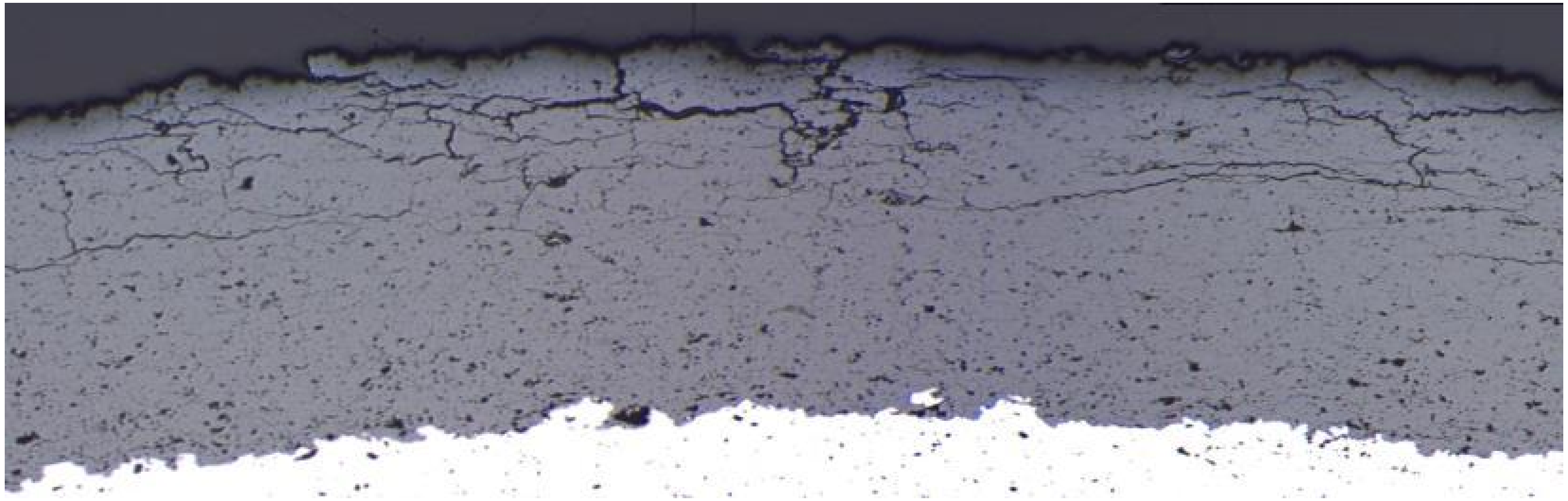


- Gradual decrease of laser power and cooling pressure up to +600 K/s suggest continuous growth of horizontal cracks
- Met confirms local damage







Presentation Outline

Introduction

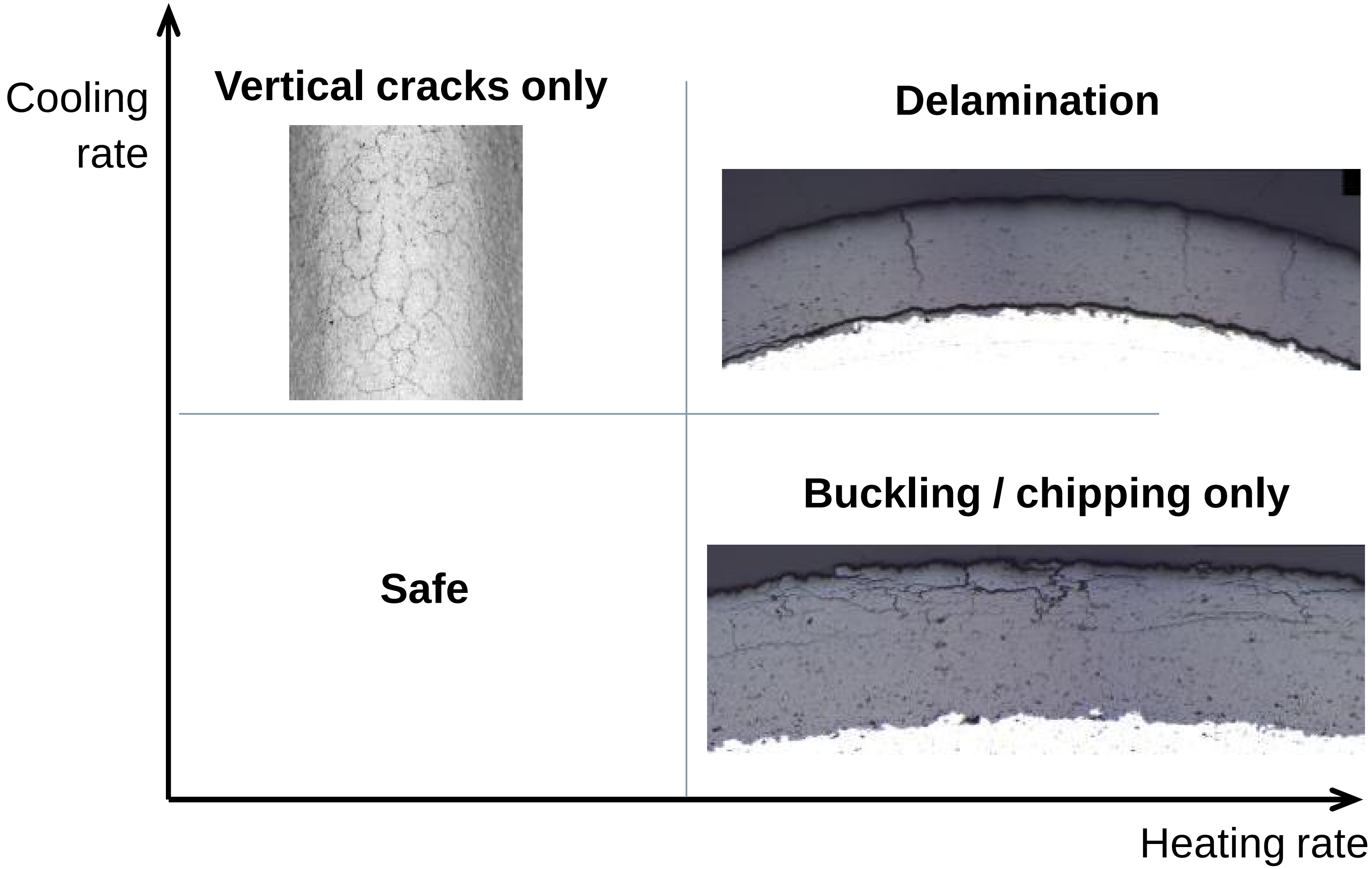
Laser-based high heat flux test bench

Distinct effects of heating and cooling rates

Failure atlas

Summary and outlook

Schematic failure atlas deduced from test results

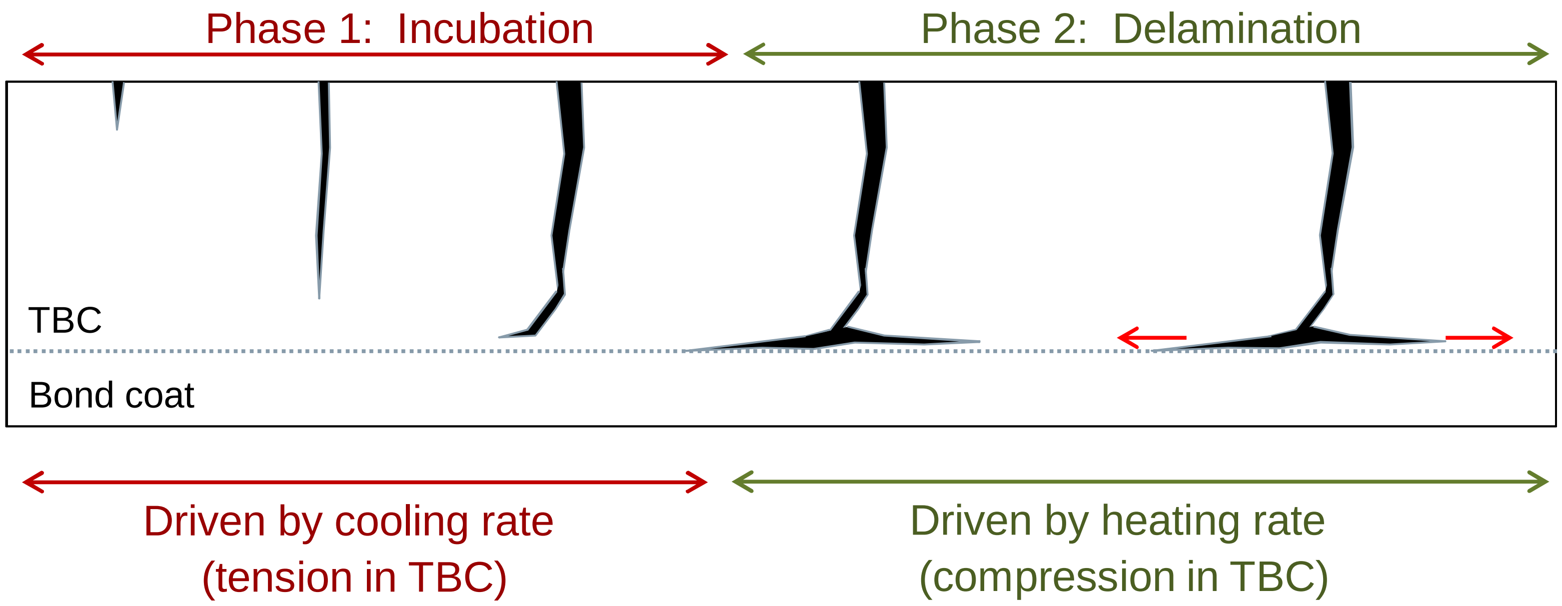


Boundaries between failure modes are affected by.

- front and back temperature
- TBC porosity
- TBC thickness

Failure atlas interpreted in terms of fracture mechanics: Two-stage process of crack formation

- Tip of vertical crack acts as a starting defect for horizontal crack formation
- TBC delamination can only occur if sufficiently long horizontal cracks have been formed



Model experiment to determine the critical heating rate in the failure atlas

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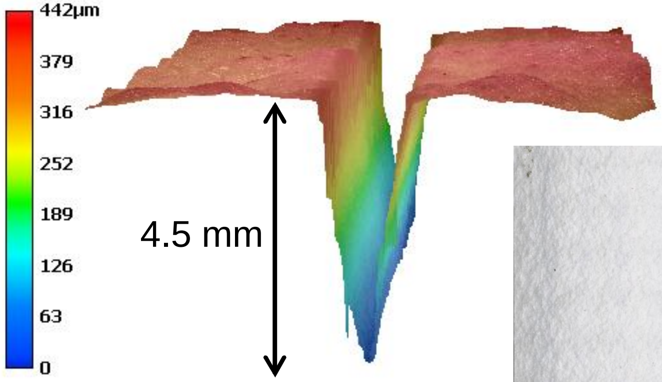
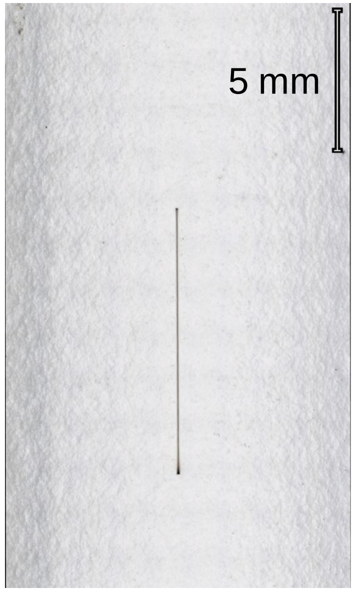
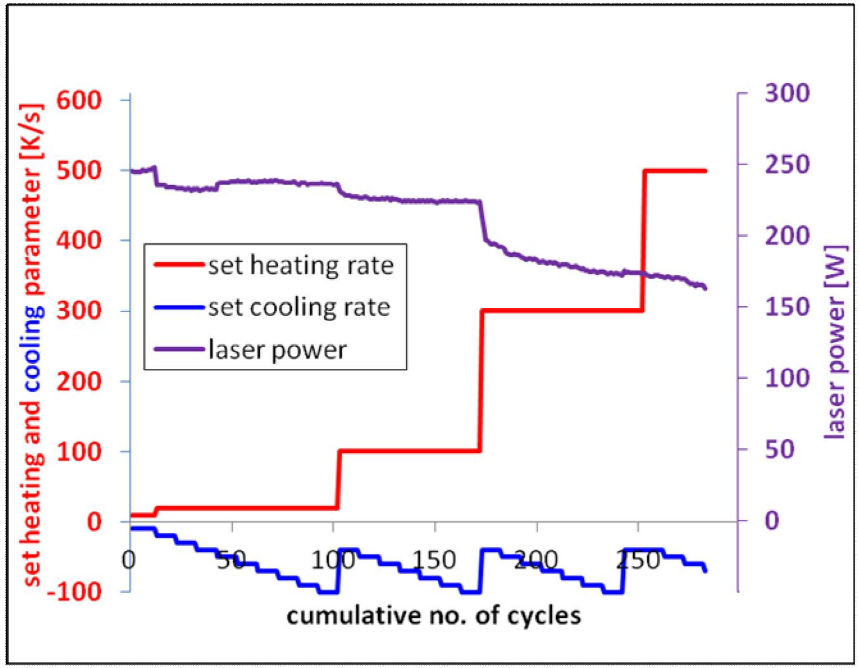
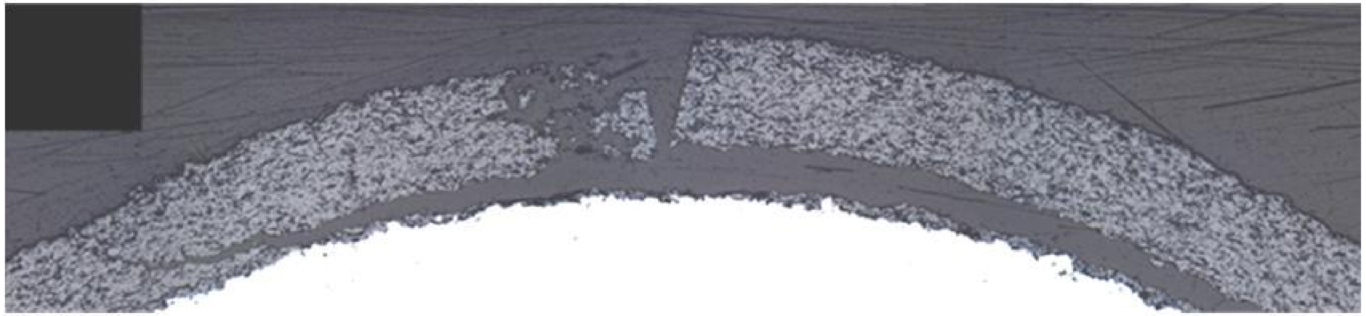
- Bypass the incubation of vertical cracks (Phase I)
- Make a notch (artificial crack) in the TBC using a ps-laser
- Notched sample fails for sufficiently high heating rate
- Cooling rate does not affect failure









Presentation Outline

Summary

Laser rig

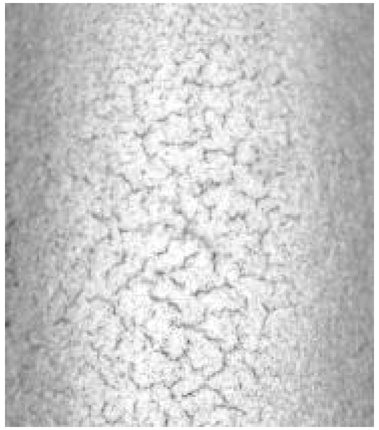
- A laser based HHFT rig is able to control heating and cooling rates very precisely
- TBC failure under high heat flux testing is strongly affected by heating and cooling rates

Only fast cooling

- A fast cooling rate on its own is not sufficient to cause failure
- When the heating rate is subsequently increased, delamination is immediate
- The sample develops deep vertical cracks in a mud-flat pattern

Only fast heating

- A fast heating rate on its own is not sufficient to cause failure
- The sample develops multiple short cracks without a clear orientation



Interpretation

- Delamination only occurs if:
  - Phase 1: Cooling is fast enough to create vertical cracks (← tensile stress in TBC)
  - Phase 2: Heating is fast enough to cause buckling (← compressive stress in TBC)
- Vertical cracks are a pre-requisite for delamination

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Outlook

- Delamination crack can grow from other defects near bond coat, bypassing Phase 1
- Example: Damage due to manufacture of cooling holes
- Laser HHFT allows different manufacturing techniques to be compared
- 8YSZ phase transformation – how important is this for TBC failure, relative to heating/cooling transients?