Thermal and Thermomechanical Operating Loads on Ceramic Heat Shields in Stationary Gas Turbines and Laboratory Simulation of these Loads

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Gas turbines are turbomachines in which several consecutive energy conversion processes take place. Chemical energy is converted to thermal energy and thermal energy into mechanical energy. Large gas turbines for power plants function as prime movers for the generator and are thus used in electric power generation. Siemens lines the combustor with solid ceramic parts (ceramic heat shields), which are manufactured from a corundum mullite base ceramic. The loading pattern is complex and includes various wear mechanisms. A test facility has been developed for part evaluation for R&D and quality assurance; this is used in thermal and thermomechanical testing at temperatures of up to 1600 °C.

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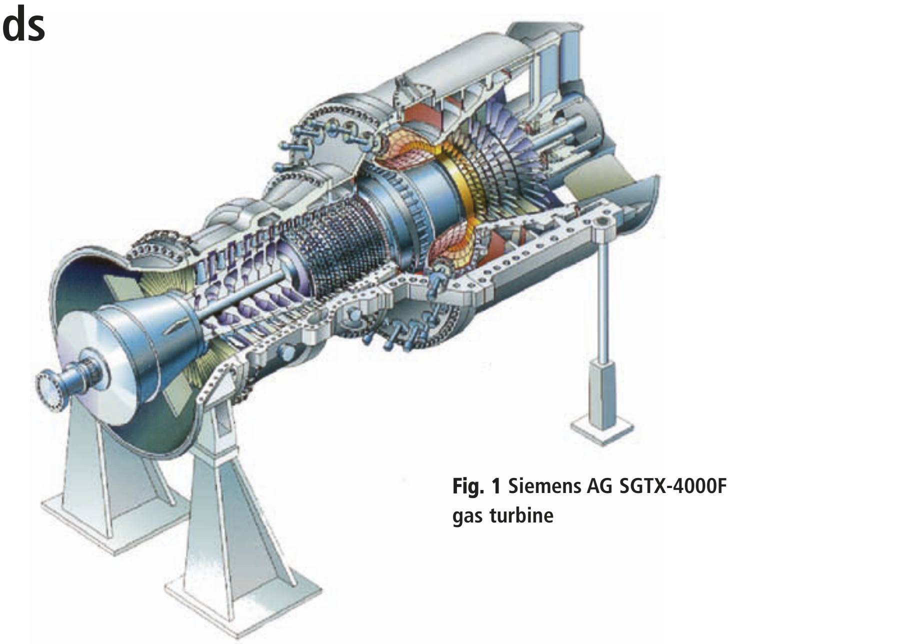

Fig. 1 Siemens AG SGTX-4000F gas turbine

1 Introduction

Stationary power plants for electric power generation are continuously operated at their allowable output and efficiency limits in order to achieve the best possible utilization of fossil fuel reserves while protecting the environment, as well as for reasons of cost effectiveness. Compliance with national and international emissions limits and the continuously increasing pressure of competition from various providers demand the continuous development of new means to optimize the machines and their components. Gas turbine and steam turbine cycles constitute the most important applications for fossil-based power generation. Fig. 1 shows an example of a *Siemens AG* gas turbine. Two design approaches are essentially available for insulating the combustor: metallic linings with ceramic coatings and solid ceramic linings.

Cooling air consumption in the combustor varies depending on the approach taken, resulting in the establishment of different surface temperatures on the parts in the hot gas path. The maximum surface temperature on the hot gas side increases from 1230 °C to > 1500 °C where ceramic heat shields are used instead of coated metallic heat shields. Since 1960, *Siemens Power Generation* has successfully implemented ceramic heat shields for insulating the hot combustor walls in gas turbines operated in stationary installations; no other manufacturer takes this approach.

The advantages of ceramic linings in comparison with open cooled metallic linings include a reduction in cooling air consumption, which results in a more uniform temperature distribution. A reduction in cooling air consumption enables a reduction in flame temperature with no change in turbine inlet temperature TIT_{iso}, which can in turn be used to reduce NO_x emissions or the surface temperatures of the parts in the hot gas path. Conversely, the potential savings in cooling air for the ceramic lining can of course also be used to increase turbine inlet temperature and thus the efficiency of the gas turbine with no change in NO_x emissions or surface temperatures, provided this is permitted by the metallic turbine components.

In order to meet the continuously increasing requirements for parameters including turbine inlet temperature and power density, the materials used had to be adapted to conditions inside the combustors. The service life of such ceramic materials is restricted by their high-temperature stability. The pressure and temperature of the hot gas, plant-specific loads such as wet compression for power augmentation and NO_x reduction as well as operator and grid requirements such as fast load changes with high temperature gradients or pressure changes are important parameters that affect wear. In addition to these parameters restricting service life, the ceramic materials are further subject to aqueous and high-temperature corrosion. The onset of corrosion causes the materials to fail primarily due to cracking, chemical corrosion and erosion. Localized melting can also occur. Ceramics which are used in combustors are thus subject to all conceivable mechanisms which can result in the failure of materials.

High thermal insulation effectiveness and high mechanical strength with optimum thermal fatigue resistance are the most important criteria in the evaluation of these materials. The continuously increasing requirements have led to the implementation of synthetic raw materials, which exhibit a significant reduction in wear-promoting contaminants. The silica content in the material was simultaneously decreased, which resulted in a reduction in the free amorphous fraction.

The following are further advantages of ceramic-lined annular combustors:

- High sustainable material temperature (lower cooling air consumption)
- Realization of so-called hot walls (homogeneous temperature distribution)
- Long service life (corrosion resistance, subcritical (controllable) crack growth, wear resistance)
- Serviceability due to compact (accessible) part dimensions (heat shields can be inspected in the installed condition, removed from the hot gas side and replaced if inspection findings indicate this is necessary)
- Lower costs for hot-gas-path parts.

2 Ceramic lining

The materials on which the ceramic heat shields are based are refractory ceramics with high corundum content.

One to two tons of ceramic material is used in a combustor, depending on its size (Fig. 2). Fig. 3 shows a standard heat shield geometry. The average heat shield size is approx. 200 x 200 x 40 mm³. The hot gas side and the cold gas side are curved to different degrees depending on the installation location. Ceramic heat shields on the hub of the annular combustor are convex, while heat shields on the outer shell are concave. As the combustor is annular and narrows towards the turbine, cylindrical or conical heat shields with different dimensions may be used depending on the combustor model. The slots in the sides aligned in the direction of flow through the combustor are used for holding the heat shield in place.

Depending on ambient conditions, the compressor outlet air has a temperature of 400– 500 °C while the flame temperature can be above 1500 °C. This results in different temperature gradients in the installed heat shields. On the hot gas side, these temperature gradients may be approx. 500 K over the circumferential or axial gap (tile edges) to the center and approx. 1000 K across the thickness of the heat shield. Two redundant metallic tile holders engage in each slot in the heat shield (Fig. 4). Each ceramic heat shield is attached to the support structure by four holders with a defined preload force and is free to expand thermally.

Gaps are established between the individual heat shields on installation to accommodate the different thermal expansion coefficients; these gaps never close completely in any operating condition. Cooling air protects the metallic holders against overheating and prevents the ingress of hot gas. This also ensures that no hot gas can flow in and reach the support structure.

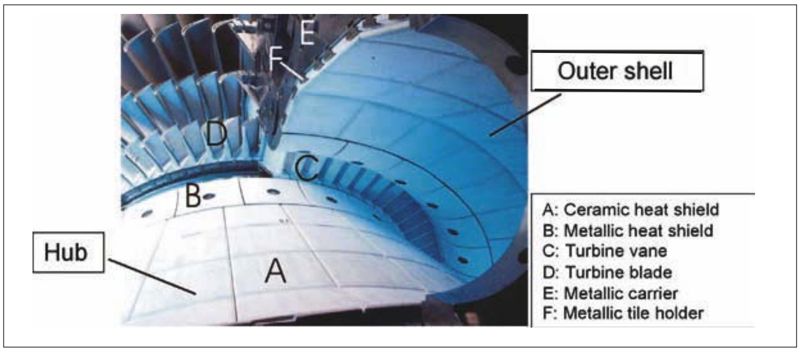

Fig. 2 **View into an annular combustor (viewed in direction of flow)**

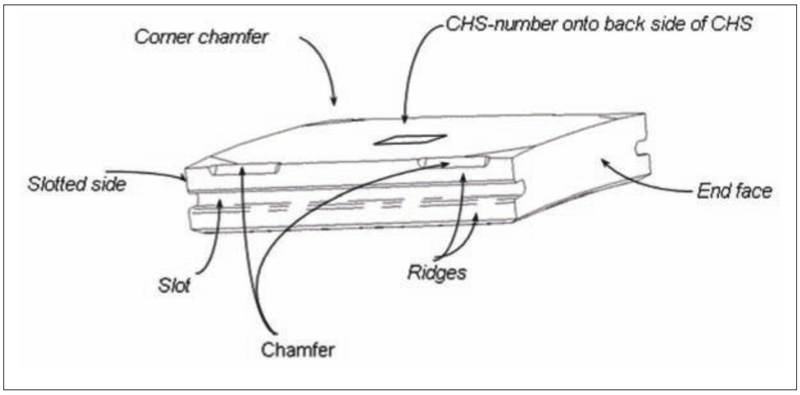

Fig. 3 **Ceramic heat shield**

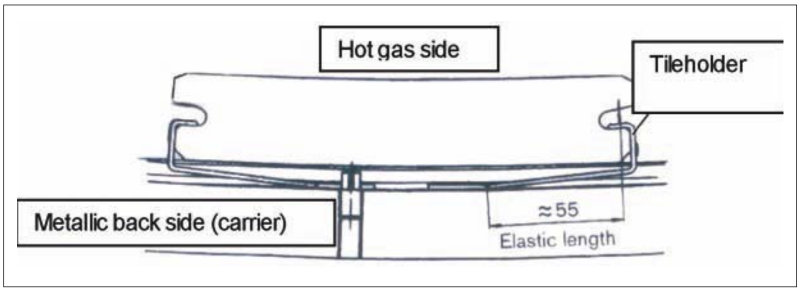

Fig. 4 **Heat shield with holders**

This system is designed such that all of the components can expand freely on heating. It is simultaneously ensured that the metal components in particular are not exposed to any excessive material-specific thermal loads. This is achieved by location of the metallic parts protected by the ceramic parts and surrounded by the flow of cooling air, as well as sufficient temperature reduction by the insulating effect of the ceramic material. The preloading of the holders is designed such that they securely hold the ceramic heat shields in position under all operating conditions, in particular on mechanical loading due primarily to vibration of the gas turbine. Prevention of the heat shields lifting off the combustor wall is a primary objective.

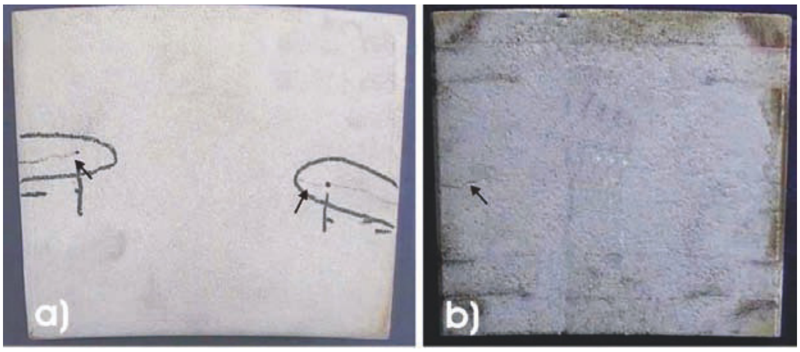

Fig. 5 Crack types in ceramic heat shields in service, a) Circumferential crack on combustor side (hot side) b) Circumferential crack on back side (cold side)

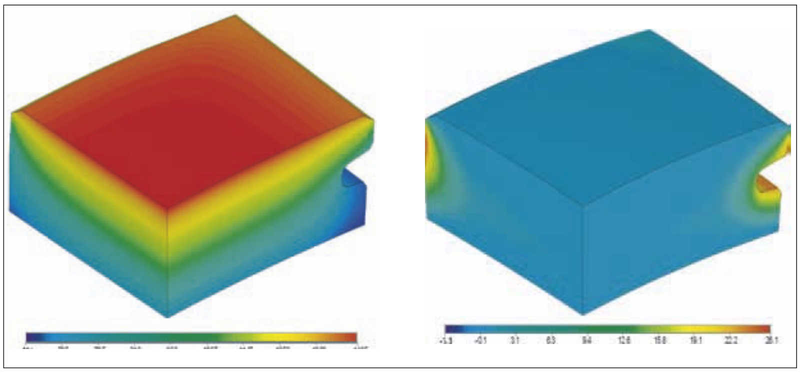

Fig. 6 Temperature and stress distribution under steady-state conditions; each view shows one quarter of a heat shield

3 Operating behaviour and loading

Heat shields develop macroscopic cracks during operation (Fig. 5). These cracks, which dissipate loads in the part, exhibit a typical pattern and limit part service life as a function of crack growth rate and crack length. The fundamental occurrence of cracks can be explained by tile geometry and temperature boundary conditions and combustion conditions in operation. This results in the thermal and mechanical loads essentially responsible for crack formation. The thermally and themomechanically induced cracks and crack growth are discussed below.

Stresses result in the heat shield due to the heat-shield specific temperature boundary conditions in the combustor. Temperature loading results in a three-dimensional temperature field in the part. The temperature gradients are aligned on the one hand from hot to cold across the thickness of the heat shield and on the other on the heat shield surface between the hot center and cold (cooled) edge. Fig. 6 shows the temperature and stress distribution in a heat shield in the steady-state condition. The stresses due to the temperature gradients across the thickness of the heat shield are dissipated or reduced by free thermal deformation. Free thermal deformation is not possible on the tile surface. The high temperature gradients on the heat shield surface therefore result in stresses which have a maximum in the centers of the edges in the direction of flow and perpendicular to the direction of flow (Fig. 6). These stresses are so great that cracks typical for this implementation form here (axial and circumferential cracks). It can be assumed that these cracks originate on the hot side. Over the course of service life, these cracks grow into a tile area with lower tensile stress. Thermal conditions prevent further crack growth at the transition from tensile stress to compressive stress in the center of the surface. Crack length is thus a direct function of maximum thermal loading and the resulting temperature gradients.

Stress maxima exceeding the material strength already occur during heating and result in initial crack formation. These cracks originate close to the hot gas side and grow in the direction of the center of the heat shield. As soon as maximum output is reached and the stresses in the part have reached their maximum, these cracks appear on the surface (Fig. 7, hot gas side, Area I). Thermal loading is compounded by further mechanical loading of the heat shields. These mechanical loads are induced primarily by pressure fluctuations in the combustor which result in continuous cyclic pressure loading in the form of high cycle fatigue (HCF). Area I (Fig. 7) is characterized by the thermally induced crack growth already described above. These cracks grow quickly, but crack growth is limited. Vibrational loading of the gas turbine results in HCF loads in the heat shield. These loads result in further crack growth of the thermally induced cracks

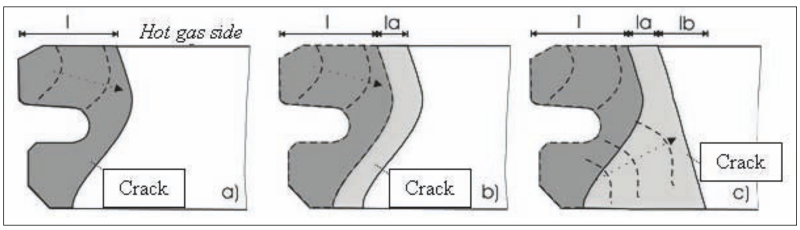

Fig. 7 Thermally and thermomechanically induced macro cracks in ceramic heat shields. Crack growth is shown in a cross-sectional view with cracks originating from the edges of the heat shield with the slot

after long operating times (Fig. 7, Area Ia). The cracks in Areas I and Ia originate close to the hot gas side. These cracks are therefore shorter on the cold side. Non-uniform pressure distribution and fluctuations in the combustor result in vibration loads. In exceptional cases where these loads are higher than the retaining forces of the metallic tile holders, the tiles lift off perpendicularly from the combustor wall and then impact against the wall. This creates tensile stress on the cold side. Development of such cracks is independent of service life, and they are longer on the cold side (Fig. 7, Area Ib).

A further crack type originates during cooldown. The hot gas side of the heat shield cools more quickly than the interior of the heat shield. This results in compressive stresses in the part and tensile stress in the center of the heat shield surface. The resulting cracks develop on the surface, and they originate there and not at the tile edges. They develop primarily under rapidly changing operating conditions in the plant. The hot side of the tile is subjected to rapid temperature changes under these operating conditions. The rapid temperature changes give rise to stress gradients across the tile cross section.

If these stresses exceed the heat resistance of the material, small cracks with lengths in the order of millimetres develop on the surface. Although these cracks have no effect on the serviceability of the heat shields, they can have a direct effect on erosion resistance due to the resulting reduction in strength of the surface matrix. These cracks are noncritical for continued use of the heat shield.

The following crack types occurring in ceramic heat shields can be distinguished by their geometry:

Axial and circumferential cracks

These cracks run from the edges of the heat shield perpendicularly towards the center of the heat shield. These cracks are caused by thermal stresses in steady-state and transient operating conditions and grow under cyclic mechanical loading (HCF) (Fig. 8). In rare cases, these cracks can also originate on the back of the heat shields.

Surface cracks

These cracks develop on the surface of the heat shield on the hot gas side, primarily under rapidly changing operating conditions in the plant (tensile stress in the center of the heat shield surface). These cracks are noncritical for continued use of the heat shield.

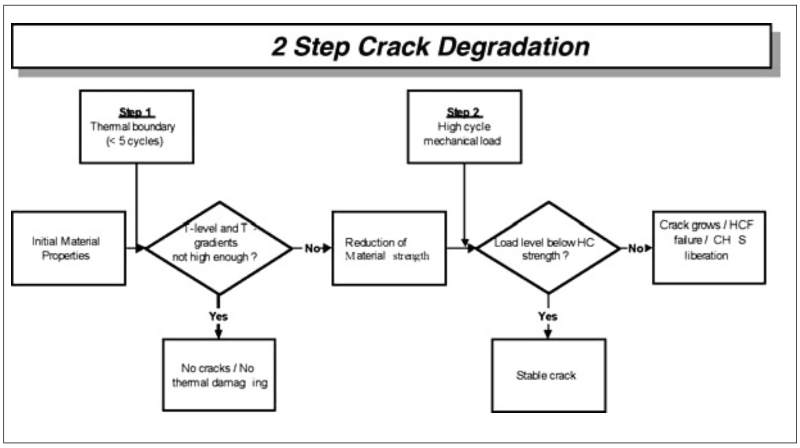

Fig. 8 Crack growth in ceramic heat shields

4 Qualification and validation

The damage mechanisms occurring in ceramic heat shields during operation and which limit service life necessitate regular inspections and the replacement of parts after many thousands of hours of operation. Typical inspection intervals are between 8000 and 12 000 operating hours or more than 1000 starts of the plant.

The objective of material development efforts for ceramic heat shields is therefore to increase both the service life and reliability of the parts.

In addition, material development must account for the higher flame temperatures and thus higher surface temperatures in the combustors of newer gas turbine models, as well as the requirement of longer inspection intervals.

The development potential in the heat shields lies in both, ceramic manufacturing as well as in the material system. The greatest challenges here lie in improving the design and further enhancement of the microstructure's strength with the objective of even higher heat resistance and thermal fatigue resistance.

Comprehensive measures for qualification and validation are implemented in order to minimize the risk entailed by introducing a new material:

1. Numerical analysis (steady-state and transient finite element calculations)
2. Laboratory testing
   a. Destructive testing (chemical, physical, mineralogical)
   b. Nondestructive examination
      i. Computer tomography (CT) and ultrasonic examination
      ii. Eigenfrequency measurement
3. Testing in the test facility (especially the thermal fatigue test facility, see below)
   a. Thermal loading at heat shield surface temperatures of up to 1500 –1600 °C
   b. Thermomechanical loading (cyclic mechanical loading at temperatures of up to 1500 – 1600°C)
   c. Long-term loading (several hundred hours)
4. Plant validation (installation of prototypes in the combustor of a stationary gas turbine).

In contrast with conventional laboratory testing (determination of hot bending strength, K_{Ic}, etc.), testing in a test facility (Item 3) has the decisive advantage of the use of entire parts instead of specially produced test blocks. This accounts for the stress component caused by the component geometry under thermal loading, the consequences of which include longer cracks perpendicular to the complex slot geometry. This method also enables investigation of the effect of the surface structure of the heat shield on crack formation (effects of a sintered surface layer, pores open to the surface, contaminants close to the surface, etc.).

The development of a thermal fatigue test facility in which both the temperature distribution as well as HCF loading during plant operation can be simulated enabled a significant acceleration in material development. Plant validation (Item 4), which represents the most time- and cost-intensive investigation, can be partially replaced by the thermal fatigue test facility. A further advantage of this test facility lies in a faster R&D phase of material development, as new materials can be immediately subjected to a test which closely simulates plant conditions and results are available within only a few days. Potential failure mechanisms in new materials can be directly investigated by specific adaptation of the test method (e.g., longer testing under mechanical load or more frequent temperature cycles).

The thermal fatigue test facility also provides an important release criterion for minor changes in the production process in the field of quality assurance for current standard materials (such as new sintering furnaces or alternative raw material suppliers), the implementation of which can thus be significantly accelerated.The replacement of plant validations with tests in the test facility as well as incorporation of the thermal fatigue test facility in the initial phase of material development (screening) yield a time savings of roughly 1 – 3 years in the introduction of new materials in the gas turbine.

5 Thermal fatigue test facility (thermal shock and thermal fatigue in entire heat shields)

The water quenching method has long been used for determining the resistance of refractory materials to cyclical thermal stresses in parts. This yields an initial indication with regard to component behavior in response to prevailing temperature gradients as well as the thermal fatigue resistance of the ceramic material. This test method cannot simulate all of the loading conditions occurring in the combustor, as this area involves fundamentally different thermal and thermomechanical loads which cause stable crack growth. In addition to the steady-state operating conditions, rapid load cycles and start-up and cooling must also be accounted for. Pressure fluctuations and part vibrations which can affect the fatigue strength of the part (HCF loads) must be anticipated in the combustor. Bending strength measurements (3-point- and 4-point bending strength) simulate static loads, which result in spontaneous failure of the test block. Mechanical loads which occur in cycles (vibrations) cannot be simulated in these tests. Siemens AG therefore developed the thermal fatigue test facility to simulate typical temperature boundary conditions which also essentially apply for ceramic heat shields in the annular combustor. This test facility enables the performance of specific thermal and thermomechanical tests on ceramic heat shields. A crack pattern develops on the ceramic heat shields which is similar to that which occurs during plant operation. These cracks develop due to the applied temperature gradients and then continue to grow as a result of additional applied oscillating mechanical loads. The schematic configuration of the thermal fatigue test facility is shown in Fig. 9. The specimen is secured with 4 holders on a combustor segment (support structure). The test block is surrounded by 6 additional heat shields. Freedom of movement to accommodate thermal expansion is enabled by specifically adjusted gaps between the adjacent heat shields. The holders are cooled from the back by compressed air. The pressure of the compressed air flow can be regulated. A heater on the hot gas side is now used to heat the specimen to a temperature of 1500 – 1600 °C. The heater is constructed with several special lamps with a total output of approx. 60 kW per heater. This enables rapid heating of an area of 200 mm x 200 mm. At the same time, a gas burner is used to heat the support structure to a temperature of approx. 450 °C. Temperature boundary conditions typical for the plant are established as shown in Fig. 9: approx. 1500 °C in the center of the heat shield on the hot gas side, approx. 1000 °C at the cooled centers of the edges and approx. 600 °C on the cold gas side of the heat shield. The support structure has a temperature of approx. 450 °C. During testing, temperature is measured directly on the surface of the heat shield using a pyrometer. Once the target temperature is reached, this temperature is maintained for approx. 30 – 90 min. The specimen is then quenched with an air spray to simulate thermal shock. Cracks that form are marked and measured on the hot gas side. Each specimen is subjected to between 1 and 50 thermal shocks. Following the thermal shocks, a ram is pressed against the back of the heat shield under temperature load with a defined preload force. The ram is vibrated (100 Hz – 500 Hz) with a maximum force which is below the preload force of the heat shield holders. This vibration test is typically performed for several hours. The thermally induced cracks previously formed can be propagated by this additional mechanical loading. The thermal shocks and mechanical loading can be varied in intensity (maximum temperature, vibration frequency and amplitude) as well as number and duration and can be adjusted for the specific material being tested.

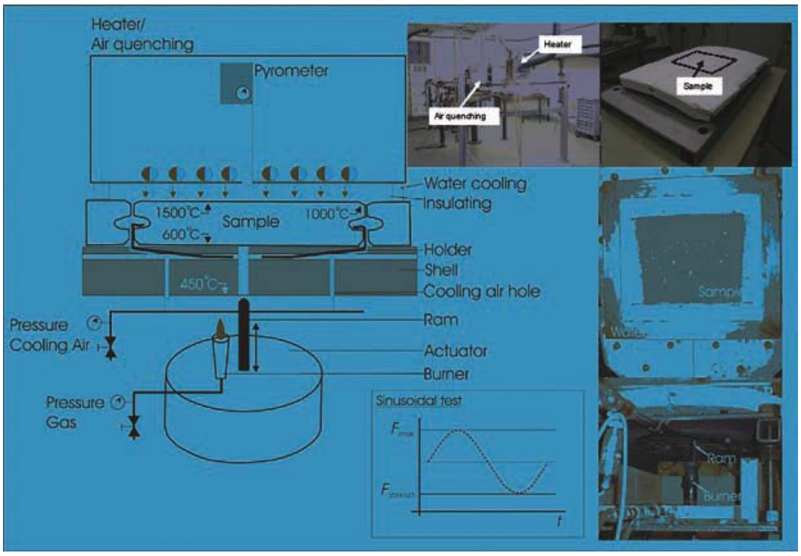

Fig. 9 Schematic setup of thermal fatigue test facility

Following nondestructive examination, the residual bending strength of the parts is determined in a four-point bending test on the entire part (Fig. 10).

6 Results and discussion

The heat shields tested in the thermal fatigue test facility are first subjected to nondestructive examination for visual determi-

Fig. 10 **Four-point bending test on entire heat shield (hot side under tensile stress)**

nation of crack length (see Fig. 11) and measurement of eigenfrequency.

Visual determination of crack length is more of a qualitative criterion, as the crack length measurement can be falsified by many factors including the following:

- Geometry of the edge crack in a (noncritical) surface crack where pinpointing the end of the crack is possible only by accounting for crack width
- Interruption of the edge crack by a coarse interstitial grain (crack bifurcation at the coarse grain, continuation beyond the coarse grain or crack arrest at the coarse grain).

The eigenfrequency measurement can be influenced by the location and geometry of the cracks relative to the point of excitation and the reading point.

However, crack length and eigenfrequency yield important supplementary criteria enabling a decision regarding the quality of the material. For example, if the eigenfrequency after loading is no longer measurable or can only be measured with difficulty (even after selecting various excitation and/or reading points), this is already an indication of severe damage to the material itself, which can then be confirmed by destructive testing.

In addition to a rough comparison with crack lengths in standard materials, determination of crack length provides an important criterion for additional examination methods, such as increasing the number of thermal shocks per specimen if the crack length curve fails to flatten out with an increasing number of thermal shocks. Atypical crack growth (such as longer cracks on the cold gas side than on the hot gas side) can also be promptly detected.

In addition to determination of crack length and eigenfrequency measurement, the specimen is examined for material detachments which are most likely to occur in the region of the tile holders and provide information on the installability of the material under typical installation conditions.

After nondestructive examination, the residual bending strength is measured (Fig. 10). Fig. 12 shows typical residual strength levels after loading in comparison with initial strength. Evaluation criteria here are not only absolute residual strength but also the scatter in the data collected as well as the mean loss of strength relative to the new condition, or the mean loss of strength under thermomechanical loading compared with strictly thermal loading. The loss of strength yields an important indication of the suitability of the material. Typical values for loss of strength are 50 – 70 %. A high loss of strength (> 80 %) can indicate an increased risk of total failure after only a few startup cycles or brief vibrational loading, even if absolute strength remains within acceptable limits.

The residual strength of the parts can be directly compared with residual strength levels for heat shields subjected to plant operation loadings. Suitable loading curves in the test facility can thus yield a specific criterion for

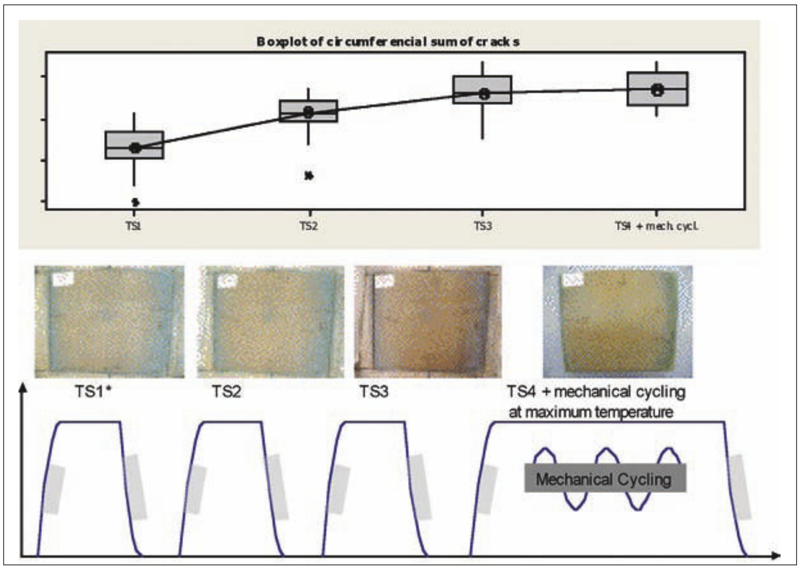

Fig. 11 **Crack formation as a function of loading in the thermal fatigue test facility; a typical test consists of three thermal shocks followed by a final fourth thermal shock during which the heat shield is cycled mechanically during the hold time at maximum temperature**

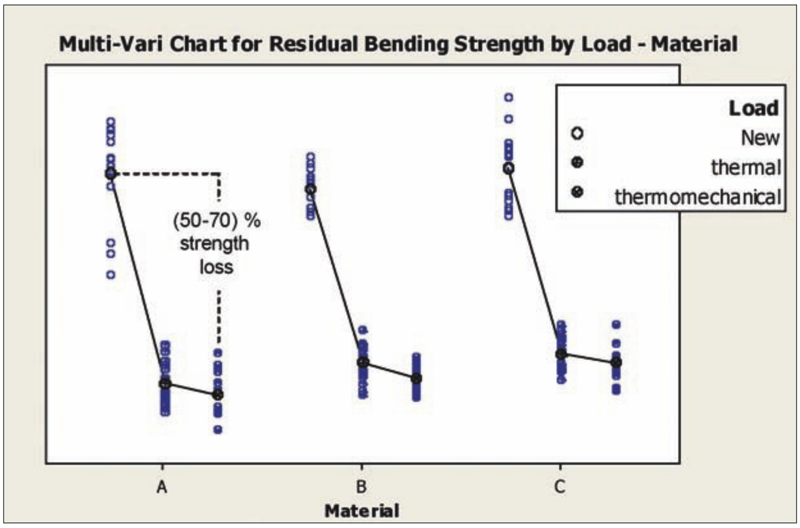

Fig. 12 **Load-dependent residual strength levels [MPa] for ceramic heat shields in the thermal fatigue test facility**

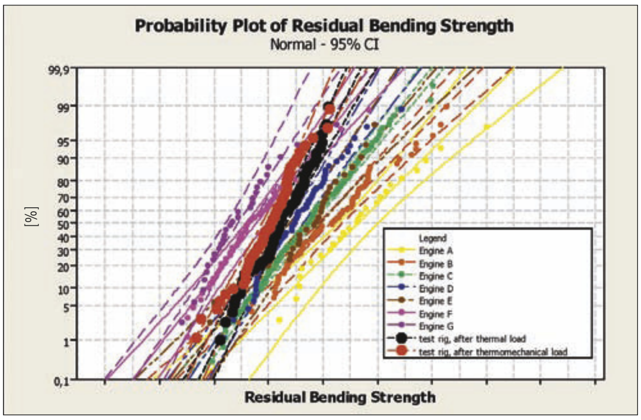

Fig. 13 **Comparison between results from thermal fatigue test facility and ceramic heat shields subjected to plant operational loadings**

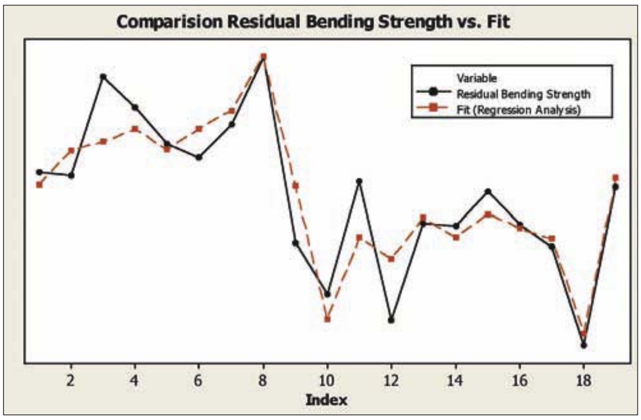

Fig. 14 **Comparison between residual bending strength of ceramic heat shields taken from a plant with calculated values (r^2 from regression analysis > 80 %) yielded by nondestructive examination (crack length and eigenfrequency)**

plant operation by loading the test heat shields in the test facility more severely (lower absolute residual strength) and with greater definition (narrower scatter) than during plant operation. Fig. 13 shows the residual strength levels recorded during tests in the test facility in comparison with various plants over several years, various plant configurations and formats. The test facility results fall within the middle to lower range of the plant data, with somewhat lower scatter than the plant data. Restricting the test specimens to a single format gives the test facility data a significantly lower scatter range, which can be attributed to the reproducible test conditions. Extremely high loads in plant conditions (such as those due to higher flame temperature, longer dynamic loading phase per inspection interval, etc., see the two far left groups of points in Fig. 13) can be simulated by increasing test facility temperature and by longer testing under thermomechanical load.

The investigation of time-dependent phenomena >> 100 h, such as high-temperature corrosion, cannot be performed in the thermal fatigue test facility. These failure mechanisms are tested either in laboratory investigations or are observed in prototype plant operation (provided no supercritical reduction in anticipated service life, similar to that in crack growth, is expected).

7 Summary and outlook

The ceramic material now used fulfills the currently imposed property requirements for high-temperature applications in the combustors of gas turbines operated in steady-state conditions. The complex profile of properties as regards grain structure, strength and the ability to withstand the extreme conditions enables its implementation as a lining material in the combustors of stationary gas turbines. Attention is drawn to the extremely high resistance to temperature cycles, which is greater than 40 thermal shocks as demonstrated during testing by the water quenching method. This test is performed on whole parts without failure involving material detachment.

The grain structure is designed such that stable crack growth occurs during normal gas turbine operation. This high resistance to unstable crack growth is due to the establishment of a grain structure, which yields a lower fracture energy in comparison with dense ceramics due to a relatively low strength and Young's modulus. The reason for this is the relatively heterogeneous structure for a material with high thermal fatigue resistance. Grain structure elements of this type result in a reduction in crack energy and arrest crack growth. They can be achieved by targeted grain structure design. The following points must be emphasized:

- Establishment of a coarse-grained multiphase grain structure with the objective of crack deflection and crack energy dissipation in large pore structures
- Establishment of high initial crack density in the form of microcracks in the grain structure; in this case, more energy is consumed in the formation of new surfaces and crack growth is inhibited
- Low glass phase fraction in the binder matrix to enhance elastic behaviour.

The thermal fatigue test facility constitutes a fast and cost-effective means of testing with conditions which are comparable to those encountered in the plant. The thermal fatigue test facility can replace costly individual tests in both R&D as well as in plant validation, and also provides an important criterion for quality assurance with the regular testing of standard materials.

One result of the investigation of residual strength levels of ceramic heat shields from plant operation was the establishment of a relationship between nondestructively examinable properties (eigenfrequency and visually determined crack length) and residual strength (Fig. 14). One development objective is to extend this relationship to more plants (with additional boundary conditions such as different temperature loads per plant) and to compare these data with the corresponding values from the test facility. The thermal fatigue test facility should thus yield not only a qualitative but also a quantitative prediction of plant behaviour (such as residual strength after a specific operating time or loading).

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