Thermal Shock Behaviour of Ceramics under Different Testing Conditions

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Abstract. Beside the presentation of interesting parts of the experimental equipment the thermal shock behaviour of two ceramics will be discussed. Specimens of silicon carbide and zirconia were investigated in air and vacuum. The influence of the testing conditions on the strength will be addressed.

1. Introduction
The use of ceramic materials is of particular interest due to the excellent strength at high temperatures, the resistance to wear and corrosion as well as the low density. In most potential fields of applications ceramic materials are also exposed to thermal shock and thermal fatigue. Due to their poor thermal conductivity thermal shock leads to high thermal stresses and to creation of micro cracks. The material or unit fails when reaching a critical level of damage. This damage may depend on the material itself or on the environmental media.

Current publications often report about quench tests to investigate the thermal shock behaviour of ceramics e.g. [1-3]. The great disadvantage of this test method is the influence of test conditions like sample shape and size, quenching media and test method used to measure residual strength on results. So the quench test is mostly of interest for qualitative comparison of materials in the field of materials research but never for dimensioning of constructions.

To overcome this limitation, different methods were developed to carry out thermal shock tests under repeatable conditions heating up by infrared lamps or by laser e.g. [4-6]. The presented thermal shock tests were carried out using laser beam heating by helical beam guidance across thin sample. The resulting temperature distribution was recorded by high-frequency infrared (HF-IR) camera. Using a vacuum-sealed test chamber, tests under different environmental media are possible. This is of great importance due to lack of publications addressing this influence.

2. Experimental
2.1 Experimental setup
Tests were carried out using thermal shock test equipment with laser beam heating. The main
feature of the test equipment is an extremely fast heating-up thermal shock resulting in high temperature gradients in thin disks using a Nd:YAG-Laser. Focusing optical system enabled helical beam guidance across the sample. Resulting temperature fields were recorded by HF-IR camera. Fig. 1 presents a sketch of the used test chamber with all important components and Fig. 2 shows the construction of the sample holder.

Some details of the test equipment are listed below:

- Nd:YAG laser with focusing optical system
  - 1 kW maximum laser power output
  - wave length $\lambda = 1064$ nm
  - continuous radiation
  - user-defined laser beam control
- HF-IR camera
  - InSb focal array $\lambda = 3$ to 5 $\mu$m
  - exposure time 2 $\mu$s up to 14 ms
  - 256 x 256 pixel, resolution 12 Bit
  - 1500 Hz
- Acoustic emission sensors
  - 150 kHz sensor with sampling rate 5 MHz
  - 32 MB memory depth
- Test chamber
  - hermetically sealed up to $4 \times 10^{-3}$ mbar
  - CCD-camera up to $\lambda = 1.1$ $\mu$m
  - Contact pin for sample fixing without obstruction of strain

2.2 Investigated materials
Investigations were carried out with the commercial ceramics zirconia (MgO-PSZ) and sintered silicon carbide. Ground samples were prepared with a diameter of 20 mm and a thickness of 0.3 mm.

2.3 Calculation of critical thermal shock strength
Laser beam heating up by helical beam guidance across the thin sample starting in the middle induces temperature profiles presented in Figure 3. Accurate space- und time resolved determination of temperature demands accurate calibration of the HF-IR camera for each material and each
environmental media so that the correlation between the readout digits of the camera and the surface temperature of the sample is known. A resulting calibration curve is presented in Figure 4.

Thermal shock strength calculations are based on the knowledge of space- and time resolved temperature fields. Provided that there is no temperature gradient through thickness direction and only elastic material behaviour occurs, the distribution of tangential stresses is calculated according to equation (1) and distribution of radial stresses according equation (2).

$$\sigma_\Theta (r,t) = E(T(r))[-\alpha(T(r))T(r) + \int_0^r \alpha(T(r))T(r) r \cdot dr + \frac{1}{r^2} \int_0^r \alpha(T(r))T(r) r \cdot dr$$

$$\sigma_{\text{rad}} (r,t) = E(T(r))\left[\frac{1}{r^2} \int_0^r \alpha(T(r))T(r) r \cdot dr - \frac{1}{r^2} \int_0^r \alpha(T(r))T(r) r \cdot dr\right]$$

Where $\sigma$ is the stress, $T$ the temperature, $r$ the radius, $t$ the time, $E(T(r))$ Young’s Modulus as a function of $T$ and $\alpha(T(r))$ the coefficient of thermal expansion as a function of $T$.

The resulting schematic trend of the distribution of calculated tangential and radial stresses at the beginning and the end of thermal shock test is shown in Fig. 5 and 6. It is supposed that failure is caused by the maximum of tangential stresses at the moment of failure so the maximum of tangential stress equates with the thermal shock strength. Radial stresses were neglected.
3. Results and Discussion
For silicon carbide and zirconia and each environmental media about 30 samples were tested. The maximum tangential stress in the moment of failure was determined as thermal shock strength. The strength distribution of ceramic samples is described by the Weibull material parameters $m$ and $\sigma_0$ and the presentation of measured strength results is given in form of a Weibull plot for silicon carbide (Fig. 8) and zirconia (Fig. 9).

Compared to test results for experiments in air there is no significant effect for testing in vacuum. One reason can be the short duration of tests, typically less than one second. It will be interesting to investigate the influence of environmental media again in fatigue tests or for materials which are known for their sensitivity to subcritical crack growth.

4. Conclusions
The presented test equipment offers the possibility to carry out repeatable thermal shock tests in different environmental media. Based on the time and space resolved measurement of temperature, failure stresses can be determined.

Thermal shock tests on silicon carbide and zirconia did not show an influence of environmental media on thermal shock strength.

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