Optical crack growth measurements applied to a refractory ceramic

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Summary

To predict the lifetime of products made of refractory ceramics, it is necessary to have a fracture model and the material parameters associated with that ceramic. Therefore some fracture tests are necessary. On the data determined with these tests a fracture model is fit.

The refractory ceramic Alcorit is used. From this ceramic three kinds test specimens are made:
- a Single Edge Notched Beam (SENB)
- a Wedge Opening Loaded (WOL) test specimen with a short notch
- a Wedge Opening Loaded (WOL) test specimen with a long notch

On these test specimens two main parameters are measured:
- the applied force to fracture the test specimen
- the Crack Opening Displacement (COD)

In previous experiments the COD was measured using a Linear Voltage Displacement Transducer (LVDT) at the opening of the notch. With this data, parameters required for a fracture model are fitted. To check this model new tests are carried out, but now the COD is measured along the crack path by the Hentchel system. This is an optical method to measure the position of a series markers on the surface of the test specimen. These markers are placed along the crack-path. With this information it is possible to improve the fracture model. In this report the measurement technique is discussed. The results of the measurements are given and compared to model predictions.
Foreword

During my Mechanical Engineering (W) study at the Eindhoven University of Technology (EUT), I have to do a training of at least 60 semi-days. I chose for a training in the group Solid State Chemistry and Materials Science (TVM), in the Department of Chemical Engineering (T). This group works together with the Department of Technical Ceramics of TNO under the name Centre for Technical Ceramics (CTK).
My assignment was to do some fracture tests on a ceramic to obtain data for validation of fracture models. For me this was an opportunity to combine practical work together with computers. Therefore I liked my training very much, and I want to thank all the people who supported me during this period.
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### Abbreviations

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<tr>
<td>COD</td>
<td>Crack Opening Displacement</td>
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<tr>
<td>CTK</td>
<td>Centre for Technical Ceramics</td>
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<td>EUT</td>
<td>Eindhoven University of Technology</td>
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<tr>
<td>FCM</td>
<td>Fictitious Crack Model</td>
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<td>LE</td>
<td>Linear Elastic</td>
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<td>LEFM</td>
<td>Linear Elastic Fracture Mechanics</td>
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<tr>
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<td>SVD</td>
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<td>T</td>
<td>Department of Chemical Engineering</td>
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<td>TNO</td>
<td>The Netherlands Organization for Applied Scientific Research</td>
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<td>TVM</td>
<td>Solid State Chemistry and Materials Science</td>
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<td>W</td>
<td>Mechanical Engineering</td>
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<tr>
<td>WOL</td>
<td>Wedge Opening Loaded</td>
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1 General introduction

The Centre for Technical Ceramics (CTK) is a joint venture between EUT and TNO within which several aspects of the use of technical ceramics are investigated. One of the research projects focuses on the mechanical behaviour of refractory ceramics. These types of ceramics are used within an oven at elevated temperatures. The use of the ceramic material can be as the bottom plate in the oven or as support for a product. In both cases the ceramic product will be heated up and cooled down several times (10-100) until it fails. This failure is a result of thermal stresses inside the ceramic product caused by the thermal gradients. The failure process due to the occurrence of these thermal stresses can be investigated using a simplification by simulating these thermal stresses by mechanical forces. This is very useful in an experimental design, because the thermal stresses are very hard to control and it is much easier to measure at room temperature than at 1200 °C.

It is not yet possibly to calculate the lifetime of all ceramic products, because some of them are made of a ceramic material with an unknown fracture behaviour. Therefore the CTK tries to find a theoretical model with makes it possible to predict the expected lifetime. For this purpose it is necessary to check the theoretical modelling of the fracture process with the reality by gathering a wide range of data of the damage process.

The examined refractory ceramic is Alcorit, produced by the company Sphinx Technical Ceramics in Maastricht, The Netherlands. This ceramic has the following properties:

\[ E \approx 13 \text{ GPa} \]
\[ \nu \approx 0.25 \]
\[ f_t \approx 5 \text{ MPa} \]
\[ \text{grain size} \approx 0.5 \text{ mm} \]
\[ \text{porosity} \approx 25\% \]

Until failure this material behaves Linear Elastic (LE). When it fails, somewhere in the material a crack initiates. This crack increases in length until the material fails. This is the unknown damage process to fit in a theoretical model. It is not known what happens at the tip of the crack or at some distance in front of the crack.
2 Fracture theories

To make any calculations on a refractory ceramic, a fracture model is necessary. The most simple and elementary theory is based on Linear Elastic Fracture Mechanics (LEFM) \[5\]. This theory assumes a crack with size \(a\) loaded with a remote stress \(\sigma\). At the tip of this crack the local stresses have an unlimited maximum. These local stresses are used in a fracture criterion. For a crack with no thickness and therefore an infinite sharp crack-tip the following analytical expression can be obtained:

\[
\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(\theta) \quad i,j=1,2,3
\]  

with \(\sigma_{ij}\) the components of the Cauchy stress tensor, \(r\) and \(\theta\) the polar coordinates at the crack-tip, \(f_{ij}\) a function depending on \(\theta\) and \(K_I\), the stress intensity factor for mode I loading. This stress intensity factor determines the magnitude of the stresses and is given by:

\[
K_I = Y\sigma\sqrt{\pi a}
\]

with \(Y\) a non-dimensional parameter depending on the size of the crack and the geometry of the test specimen. This formula is very general applicable for all kinds of structures. For mode II and mode III loadings similar expressions can be obtained for the stress intensity factors. In materials for which LEFM is valid, catastrophic crack growth resulting in fracture occurs when \(K_I\) reaches a critical value \(K_{IC}\). This critical stress intensity factor or fracture toughness \(K_{IC}\) is an experimentally determined material property.
According to the LEFM theory the stresses near the crack tip are infinite (see figure 1). This is a result of the fact that material nonlinear effects are not taken into consideration. For a (brittle) material with a small nonlinear zone in comparison with the total size of the structure, the LEFM gives a good description of the mechanical behaviour [6]. LEFM is, however, not applicable for materials with a relative large process zone in front of the crack tip. This process zone causes a Nonlinear Fracture Mechanics (NLFM) behaviour (see figure 2). This NLFM behaviour occurs at small specimens and at material with a $K_{IC}$ dependent on the crack length. Such a material is Alcorit [4].
There are several models to take into account the existence of a process zone. At the moment the model of Hillerborg [2] called the Fictitious Crack Model (FCM) is used. The crack geometry of this model is shown in figure 3. A part of the crack still carries a part of the load. The constitutive function of this part of the crack has to be determined by experiments. Figure 4 shows some possible shapes of that function. The area under such a curve equals the fracture energy $G_f$ of the material:

$$G_f = \int_0^{\alpha} \sigma_N du_N$$  \hspace{1cm} (3)

The shape of this $\sigma_N - u_N$ curve is dependent on the material. The experiments which have been conducted to determine this shape are presented in chapter 3.
3 Description of the experiments

This chapter will describe the used test geometries and the used test equipment. Also the total test configuration will be described.

3.1 Stable and unstable tests

Stable fracture mechanics tests are necessary to determine some fracture mechanics properties. Especially the behaviour of the test material during crack growth is important. Stable tests make measurements much easier.

![Figure 5]

A test is stable if no sudden drop of the load occurs. In figure 5 the measured force-time curves of a stable and an unstable test are plotted. These figures are a result of tests carried out by a constant speed of the actuator of the testing machine. The drop of the load occurs after reaching the peak load. The specimen and the test machine both have stored elastic energy while loading. This stored energy is released after reaching the maximum applied force. During a stable fracture test, a gradual release of this elastic energy occurs after reaching the peak load. During an unstable fracture test, this elastic energy releases all at once. This energy accelerates the fracture process.
Compare this effect with the model in figure 6.

![Figure 6](image)

The spring is moved with a constant speed and pushes against the block. At a certain point, the force of the spring is equal to the force of friction, and the block will start to move. If the static and dynamic coefficients of friction are not equal, the spring will release to a new equilibrium. The released energy accelerates the block.

In case of a fracture test, the testing machine will release the stored energy when the test specimen fails. If the stored energy is more than needed for fracturing the test specimen, the test specimen will fail faster than intended. If the testing machine is stiffer, it stores less energy (see figure 7 and equation 4) and above a certain stiffness, the test will be stable.

![Figure 7](image)

\[ F_s = k \cdot u_s \]

\[ W = \frac{1}{2} k \cdot u_s^2 = \frac{1}{2} \cdot \frac{F_f^2}{k} \]  \hspace{1cm} (4)
When the test specimen is less stiff, the test also tends to be more stable. Brühwiler and Wittmann [1] investigated the criterion for obtaining stable tests and derived equation 5 using some simplifications:

\[ l_{ch} > K \cdot L \cdot \left( \frac{k_p}{k_H} + 1 \right) \]  
\[ l_{ch} = \frac{E \cdot G_f}{f_t^2} \]  

(5)

where \( l_{ch} \) is the characteristic length of the material, \( K \) is a constant depending on the specimen geometry. In an uniaxial tensile test, \( L \) is the specimen length. For bending specimens, \( L \) is the cantilever (wedge) or the span (beam). Furthermore \( k_p \) is the specimen stiffness and \( k_H \) is the stiffness of the testing machine. As mentioned before, this equation is based on simplifying assumptions and is only meant as a global criterion for a stable fracture test.
3.2 The Wedge Opening Loaded test

The Wedge Opening Loaded (WOL) test is a stable fracture test used for concrete and concrete-like materials such as rock and ceramics. The specimen geometry for this test is shown in figure 8.

![Figure 8](image)

The test specimen is placed on two rollers. At the top of the test specimen, two axles with bearings are placed in the holes. Between these bearings a vertical force pushes a wedge forcing the axles to separate (see figure 9).

![Figure 9](image)

This force is a result of the displacement controlled movement of the wedge and the resistance of the test specimen. While fracturing, the pre-crack starts to increase in length.
The wedge transforms the vertical force into horizontal forces acting on the axles. The friction within the bearings is very small (friction coefficient < 0.01) and therefore negligible. Figure 10 illustrates the balance of forces.

\[ F_h = \frac{F_v}{2 \tan \beta} = 1.866 F_v \quad \beta = 15^\circ \]
3.3 The Single Edge Notched Beam test

The Single Edge Notched Beam (SENB) test is an often used test in fracture mechanics. The test configuration is shown in figure 11.

![Figure 11](image)

The test specimen is placed on two rollers. Above the pre-crack a force pushes another roller against the SENB.
3.4 The Hentchel system

The Hentchel system is an optical measurement system. It is mostly used for experiments on synthetic (polymers) and organic (skin) materials. It measures displacements in a 2D or 3D view. For the WOL and SENB tests only a 2D measurement with one camera is necessary. For a 3D measurement two cameras are needed. The Hentchel system consists of 3 main parts:

- a random access camera:
  This is a special camera, which scans not like a normal camera the whole view with a standard pattern, but scans over an user defined path only a part of its view. This increases the measuring speed substantially.

- controlling equipment:
  The controlling equipment controls the camera and converts the data from the camera into data suitable for the computer.

- a computer:
  The computer tells the controlling equipment what to do and stores the data from the controlling equipment.

![Figure 12](image)

On the test specimen (light) retro-reflecting markers are placed. Figure 12 illustrates two possible marker patterns. These markers are made by punching a retro-reflecting sticker with a needle (inside diameter 0.5mm - 2mm). A set of bright lamps shines on these markers and the markers reflect the light back to the camera. The Hentchel system scans a total window of 32768 x 32768 pixels with a speed up to 7500 Hz. If the camera scans a total window of 100 mm by 100 mm at a distance of 1 m, the accuracy is about 0.01 mm. Within that window a maximum of 127 markers can be measured. The camera first scans the whole window.
(see figure 13) to recognizes the position of the markers. With the position of the markers in the actual test known, only a small box around each marker has to be scanned.

![Figure 13](image)

If the position of a marker changes, the controlling equipment moves the box of that marker with it. A marker is lost, when it moves between the measuring intervals out of the box. To prevent this, a higher measuring speed must be chosen (a larger box around a marker decreases the measuring speed). A higher measuring speed means also a less accurate measurement. This is a result of the internal working of the Hentchel system. Another important restriction is the maximum data the computer can store (only 128k). As a result there is only room for a specific number of data points. A high number of markers or a fast measuring speed, reduces the total possible measuring time for a test:

\[
\text{Data points} = \text{time} \times \frac{\text{points}}{\text{time}}
\]

\[
\leq \text{Max}_{\text{data points}} \leq 32768
\]

The computer stores the positions of all the markers against the time. These positions are given in pixels. The pixels must be transformed into a distance. Therefore a reference of two markers with a known distance between them is required. Because the distance between the reference markers is known and the number of pixels is measured, the transformation factor can be computed.
3.5 The total test configuration

During this test two main parameters are measured. One of them is the applied force and the other one is the Crack Opening Displacement (COD). During earlier measurements, the COD was measured with a Linear Voltage Displacement Transducer (LVDT) as shown in figure 14. With this information the material parameters of a theoretical fracture model are determined. With the grid of markers on the test specimen, COD’s along the crack path are measured using the Hentchel system. This data is used to compare it with data from the theoretical fracture model.

![Figure 14](image)

In the test also the displacement of the wedge is measured. This is done in two ways: first the displacement is measured at the same time as the applied force, second some markers are placed on the support and the displacement is measured with the Hentchel system (see figure 15). The two horizontal arms measure the displacement of the wedge. On the black supports in front of the WOL specimen, the markers are placed to determine the displacement of the wedge with the Hentchel system. These data points are used to determine the time difference between starting of the fracture test and starting of the Hentchel system.
In spite of careful and accurate placement of the test specimen and the rollers, it is important that the test specimen is placed under an initial load before the fracture test begins. This initial force pushes the test specimen in place. It was also necessary to wiggle the test specimen manually to position the support rollers and the axles correctly.
4 Results

All the data from the tests were stored in a computer. These data points are processed within a software packet called Matlab, a flexible mathematical package with a build-in symbolic language. This is done in a few steps as described in the following paragraphs.

4.1 Filtering the data

Before the data from the Hentchel system can be used, it has to be filtered to reduce the noise. There are two filters used: the Singular Value Decomposition (SVD) filter and the Butterworth filter. Also a combination of these filters is used. The results of these filters are shown in figure 16. The signals are shifted vertically for a better overview.

The SVD filter is based on linear algebra [3]. A real matrix A (this is the measured data) can always be written like A=Q₁*S*Q₂ᵀ. S is a diagonal matrix with the singular values of A along its diagonal, starting at the left top with the biggest value down to the smallest value at the right low position. Q₁ and Q₂ are orthogonal matrices. Filtering happens by leaving the smallest values within S away and A is calculated back by A=Q₁*S*Q₂ᵀ. The new A is now filtered. A way to determine how many singular values can be left out is by plotting the original signal and the new filtered signal. When the filtered signal is not getting better, the limit is reached. If more singular values are left out, the filtered signal is deviating from the unfiltered signal. The limit for the SVD filter is now reached.
The Butterworth filter is totally different. It is a digital low-pass filter that uses a N'th order filter and a cut-off frequency. The optimum parameters for this filter are determined visually using the frequency spectrum of the measured signal. The used filter is a first order filter with a cut-off parameter of 0.05. This cut-off parameter is a value between 0 and 1 with 1 corresponding to half the sample rate. Figure 17 illustrates the effect of the order and cut-off parameter of the Butterworth filter.

![Figure 17](image)

From the top to the bottom the signal is filtered more severely. The used parameters from top to bottom are:

1e order 0.1 cut-off parameter
2e order 0.1 cut-off parameter
1e order 0.05 cut-off parameter
2e order 0.05 cut-off parameter

The signals are shifted vertically for a better overview. The Butterworth filter has one important disadvantage. The values of the first and last point of the data are fixed. The values close to them are fit to them, so if a line would be drawn through the data, the beginning and ending of the line would not be lying on the true positions. See figure 16 for an explanation. The begin and end values of the data and close to them are not usable. There are two methods to prevent this: first it is possible to place the first measured position by hand on the expected position. This must be done for all first x and y position of each marker. This is a lot of work and the possibility for making mistakes is large. The second method is to filter the signal first with SVD filtering and thereafter with the Butterworth filter. This is the double filtered signal shown in figure 16. By using first the SVD filter, the amplitude of the noise decreases. A result of this is also that the first and last point of the data lie more on the expected average position. The Butterworth filter removes the remaining noise. This double filter method is used for processing the measured data.
4.2 Processing the data

After the data is filtered, the data from the Hentchel system is converted from pixels to a distance in mm. This distance always is taken between two markers. This is done by using the known distance in pixels and mm from the reference as mentioned in paragraph 2.4. See figure 18 for the situation. Because the reference is placed in front of the test specimen, also the reference distance has to be corrected. With equation 8 the true distance in mm can be calculated.

\[
\tan(\alpha) = \frac{B}{A} = \frac{D}{A+C} \Rightarrow D = \frac{(A+C)B}{A}
\]

Figure 18

To convert the pixels to mm the next calculation is necessary:

\[
\frac{\Delta_{\text{ref pixels}}}{\Delta_{\text{ref mm}}} = \frac{\Delta\text{pixels}}{\Delta\text{mm}} \Rightarrow \\
\Delta\text{mm} = \frac{\Delta_{\text{ref mm}}}{\Delta_{\text{ref pixels}}} \times \Delta\text{pixels}
\]
Combining equations 8 and 9 gives the real distance between two markers.

As mentioned in paragraph 3.5 the time difference between starting the test machine and the Hentchel system has to be determined.

**Figure 19**

Figure 19 shows an example of the two measured displacements of the wedge plotted against the time. The horizontal distance between the right smooth line (measured synchronous with the force) and the line with noise (measured with the Hentchel system), is the time difference between starting the fracture test and the Hentchel system. Fitting both lines on each other is done by taking the least squares solution. The left smooth line is corrected with the time difference.

Finally one operation is still necessary. The applied force and displacement from the support are measured with a different frequency than the displacements measured with the Hentchel system. This data has to be synchronized. The applied force and the displacement are measured with a higher frequency then a total field of markers with the Hentchel system. There are now two possible procedures to synchronize the data. It is possible to use the frequency of the measured force and displacement of the support or the measured frequency of the displacements with the Hentchel system. Chosen is for the last possibility, because of accuracy. For every measurement from the total fields of markers, there is always a measurement of the applied force and displacement of the support which lies very close to it. The data from that point is taken. It is possible to interpolate, but because of the small error and high speed by taking the closest value this is not done. The frequency of the Hentchel system is about 4.5 Hz and the frequency of the measured force is 33.3 Hz.
4.3 Checking the data for reliability and usability

There were 14 measurements performed, 3 SENB tests and 11 WOL tests. They are called BALKA through BALKC and WOLA through WOLK. From those 11 WOL tests, 3 are with a long notch (a=0.5). In the 8 WOL tests with a short notch (a=0.25) the thickness of the specimens are not all the same. Also the tests are carried out on 3 different test machines. First one WOL test was performed on a testing machine at CTK to check whether the Hentchel system could be used on Alcorit. The results of this test were positif, so more tests are done on two other testing machines. See appendix I for more information concerning which tests were performed on which machine, with which conditions, etc.

An important plot to check the tests is the applied force against time. See figure 20 for this graph of test WOLB.

![Figure 20](image)

**Figure 20**

Compare this graph with figure 21 of test WOLG.

![Figure 21](image)

**Figure 21**

Although the test geometry is the same, the graphs are different. Test WOLB has not fractured stable. The only difference between these tests are the applied speed of the wedge and the used test machine. In earlier tests the
influence of the applied speed was checked [9]. Between 0.2 and 5.0 mm/min no difference could be detected. The used speeds for WOLB (1.5 mm/min) and WOLG (0.5 mm/min) are within that range. The only good explanation for the observed difference can be found in the testing machines (see also equation 5). The WOLB specimen is tested on a machine with a loadcell of 5 kN. The geometry of this loadcell is a bending beam (see figure 22). The WOLG specimen is tested on a machine with a loadcell of 10 kN. This loadcell lies straight in line with the applied force (see figure 22).

![Diagram of loadcells](Image)

*Figure 22*

Experienced users of both testing machines mention that a loadcell in line with the applied force is 10 times more stiff than a loadcell in form of a bending beam of the same range. No big error is made by assuming that only the loadcell determines the stiffness of the total testing equipment of the testing machine. So test WOLG is done on a testing machine that is 20 times stiffer. This assumption is not verified by tests.

The three SENB tests and some WOL tests are made on the testing machine with the bending loadcell. All these fracture tests where not stable. Only the data until the specimen fractures is usable. There is no usable data concerning the actual crack growth process of the test specimens. All the following results of tests are from the most stiff testing machine (WOLG through WOLK).
Two kinds of pattern of markers are used (see figure 12). The first tests had a full field of markers. A plot is made of the change of distance between two columns of markers, without a crack between. This is shown in figure 23. The position is explained in figure 24. Every time step is a single measurement of all the markers.

The material is too stiff to measure a change in elastic displacement over such a small distance with the Hentchel system. The result of this is that only the data of one column of markers on each side of the crack is used. It is no longer necessary to put a whole grid of markers on the test specimens. This has two advantages: first it requires a lot of time less to put only two columns of markers on the test specimen and second more measurements can be done in the same time while fracturing (limit computer of 128k).
4.4 Graphical representation of the results

In paragraph 3.3 some results already were shown. Figure 23 is only a check. In figure 25 the same kind of graph is shown but now with the crack between two columns of markers.

![Figure 25](image)

This 3D graph is not easy to interpret, so cross-sections are made over the time-axis and position-axis.

![Figure 26](image)

In figure 26 a cross-section is made at a particular time. At the position of the pre-crack (top position), the crack is wide open. As expected at the bottom the COD is less. The line is almost straight. At a particular time, the visible tip of the crack is at a specific position. From the top to that position, the COD must be greater than zero. Below that position, the COD must be equal to zero. See figure 27 for this model. This model is not found within any cross-section for a particular time.
In figure 27 a cross-section is made for a particular position.

After a certain time the tip of the crack crosses the measured position and the COD for this position increases.

In figure 29 all these cross-sections of each position are plotted within one graph. The speed of the crack growth can now be determined by taking the horizontal difference between each line and the known distance between two positions.
So far the results of the Hentchel system and the testing machine are separately used. A combination is the Force-COD graph for each position along the crack. In figure 30 this graph is shown for the top and bottom position.

![Figure 30](image)

The force decreases as the crack at the top position starts to grow. At the bottom position the crack arrives after some time. The COD at that position starts to increase as the applied force already has passed its maximum.

![Figure 31](image)

All previous graphs also can be made for the WOL tests with a long notch. In figure 31 the applied force against time of WOLG and WOLK are shown. The maximum applied force for the long notch, is less and the stiffness is also less as could be expected.
Figure 32 shows the same graph, but now with all the stable tests together.
4.5 Comparing the data with the theoretical fracture model

Based on earlier measurements with a LVDT, a theoretical fracture model is formulated. The results of that model must be checked using the measurements of the Hentchel system. In this paragraph those results for a WOL specimen with a short notch will be checked. In figure 33 the calculated force against time is shown. Also the results of WOLG are shown. For the theoretical fracture model a bi-linear constitutive relation is used with:

\[ f_t = 3.4547 \text{ N/mm}^2 \]
\[ \alpha = 0.2503 \]
\[ \beta = 0.1570 \]
\[ u_{cr} = 0.0604 \text{ mm} \]

\( \alpha \) and \( \beta \) determine the shape of the bi-linear function as shown in figure 4.

In figure 33 the COD against the horizontal force are shown for the top and bottom position. Because this graph is independent of time, it is the best comparison between the calculated data and the measured data.

![Figure 33](image)

On the same kind of graph as figure 33 the theoretical model is fit, but then with the COD measured with the LVDT. For the top position (most right graph) this graph fits very well, although a part of the measured COD is elastic deformation. The calculated COD is the true COD without elastic deformation. When the position lies closer to the LVDT position, its graph should resemble the measured graph with the LVDT. The graph for the bottom position fits less good. This graph is magnified in figure 34.
Initially the COD is negative due to elastic deformations (compressive stresses in the bottom part of the specimen). These elastic deformation are not included in the calculated (theoretical) data, making a comparison of the data difficult.
To show the variation between the two stable WOL tests with a short notch, the next two graphs are shown.

**Figure 35**

**Figure 36**

Figure 35 shows the COD-F curves for the top position and figure 36 shows the COD-F curves for the bottom position. The variation between the two measurements is limited in view of the relatively small displacements.
In figure 37 and figure 38 the same kind of graphs are shown of the stable WOL tests with a long notch.

Figure 37

Figure 38

The quality of the calculated data of a test specimen with a short and a test specimen with a long notch are very similar.
5 Conclusions and recommendations

The Hentchel system is well suited for measuring crack growth in the ceramic material used. Compared to the LVDT measurement, it gives more information along the path of the crack. With this additional information it is possible to fit the theoretical model better to the reality. For a better comparison it is necessary to calculate new data, including elastic deformation.

The accuracy of the measurements is about 0.01 mm. This is too small to measure a change in distance between markers in the grid of figure 12b, without a crack between. Therefore only one column markers on each side of the crack is necessary.

SENB tests on the stiff testing machine could be stable. New tests are necessary to check this. Also the stiffness of all used testing machines must be measured to check equation 5. If this equation is reliable, it is usable for other fracture tests.

Finally it can be concluded that the theoretical model roughly fits the experimental data, but more testing and modelling must be done before the model is useful for practical use.
Literature


Appendices
WOL1

Testing machine: CTK Erichsen 10 kN  1.5 mm/min
Maximum applied force: not measured
Tforce to force: not measured
Tframe to frame: 0.4779 sec

Hentchel system:
cam  2
window 1.4 %
nmarc 112
fsam  937.5 Hz
transfr 4
llim  0
rlim  4095
step  11
camera lens 100 mm (2x50 mm)
distance lens-object 890 mm
distance ref.-object 11 mm
reference 40.32 mm

Test specimen:
Thickness 30 mm
Notch  60 mm
WOLB

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing machine:</td>
<td>WFW Zwick 5 kN 1.5 mm/min</td>
</tr>
<tr>
<td>Maximum applied force:</td>
<td>684.6 N</td>
</tr>
<tr>
<td>Tforce2force:</td>
<td>0.02 sec</td>
</tr>
<tr>
<td>Tframe2frame:</td>
<td>0.5291 sec</td>
</tr>
</tbody>
</table>

Hentchel system:
- cam 2
- window 1.4 %
- nmarc 124
- fsam 937.5 Hz
- transfr 4
- llim 0
- rlim 4095
- step 9
- camera lens 100 mm (2x50 mm)
- distance lens-object 920 mm
- distance ref.-object 9 mm
- reference 40.32 mm

Test specimen:
- Thickness 28 mm
- Notch 60 mm

Note:
Markers on wedge touched an axle during the fracture test.
WOLC

Testing machine: WFW Zwick 5 kN 1.5 mm/min
Maximum applied force: 625.6 N
Tforce2force: 0.02 sec
Tframe2frame: 0.4736 sec

Hentchel system:
cam 2
window 1.4 %
nmarc 111
fsam 937.5 Hz
transfr 4
llim 0
rlim 4095
step 8
camera lens 100 mm (2x50 mm)
distance lens-object 920 mm
distance ref.-object 9 mm
reference 40.32 mm

Test specimen:
Thickness 27 mm
Notch 60 mm
WOLD

Testing machine: WFW Zwick 5 kN 1.5 mm/min
Maximum applied force: 764.4 N
Tforce2force: 0.02 sec
Tframe2frame: 0.1280 sec

Hentchel system:
cam 2
window 1.4 %
nmarc 120
fsam 937.5 Hz
transfr 1
llim 0
rlim 4095
step 8
camera lens 100 mm (2x50 mm)
distance lens-object 920 mm
distance ref.-object 9 mm
reference 40.32 mm

Test specimen:
Thickness 30 mm
Notch 60 mm

Note:
The Hentchel system was started during the fracture test at about a force of 600 N.
WOLE

Testing machine: WFW Zwick 5 kN  1.5 mm/min
Maximum applied force: 771.7 N
Tforce2force: 0.02 sec
Tframe2frame: 0.0597 sec

Hentchel system:
cam 2
window 1.4 %
nmarc 56
fsam 937.5 Hz
transfr 1
llim 0
rlim 4095
step 8
camera lens 100 mm (2x50 mm)
distance lens-object 920 mm
distance ref.-object 9 mm
reference 40.32 mm

Test specimen:
Thickness 30 mm
Notch 60 mm

Note: The Hentchel system was started during the fracture test at about a force of 620 N.
WOLF

Testing machine: WFW Zwick 5 kN  1.5 mm/min
Maximum applied force: 789.1 N
Tforce2force: 0.02 sec
Tframe2frame: 0.0597 sec

Hentchel system:
cam 2
window 1.4 %
nmarc 56
fsam 937.5 Hz
transfr 1
llim 0
rlim 4095
step 8
camera lens 100 mm (2x50 mm)
distance lens-object 920 mm
distance ref.-object 9 mm
reference 40.32 mm

Test specimen:
Thickness 30 mm
Notch 60 mm

Note:
The Hentchel system was started during the fracture test at about a force of 620 N.
WOLG

Testing machine: WFW-Polymer Zwick 10 kN 0.5 mm/min
Maximum applied force: 683.4 N
Tforce2force: 0.03 sec
Tframe2frame: 0.2219 sec

Hentchel system:
cam 2
window 1.4 %
nmarc 26
fsam 937.5 Hz
transfr 8
llim 0
rlim 4095
step 10
camera lens 100 mm (2x50 mm)
distance lens-object 922 mm
distance ref.-object (top) 6 mm
distance ref.-object (bottom) 3 mm
reference 22.91 mm

Test specimen:
Thickness 30 mm
Notch 60 mm

Note:
The top reference is placed on the wedge.
Testing machine: WFW-Polymer Zwick 10 kN 0.5 mm/min
Maximum applied force: 706.6 N
Tforce2force: 0.03 sec
Tframe2frame: 0.1109 sec

Hentchel system:
cam 2
window 1.4 \%
mmarc 26
fsam 937.5 Hz
transfr 4
llim 0
rlim 4095
step 12
camera lens 100 mm (2x50 mm)
distance lens-object 923 mm
distance ref.-object (top) 7 mm
distance ref.-object (bottom) 15 mm
reference 22.91 mm

Test specimen:
Thickness 30 mm
Notch 60 mm

Note:
The top reference is placed between the loadcell and the wedge.
The Hentchel system is started about 10 seconds later.
WOLI

Testing machine: WFW-Polymer Zwick 10 kN 0.5 mm/min
Maximum applied force: 362.8 N
Tforce2force: 0.03 sec
Tframe2frame: 0.2219 sec

Hentchel system:
cam 2
window 1.4 %
mmarc 26
fcam 937.5 Hz
transfr 8
llim 0
rlim 4095
step 12
camera lens 100 mm (2x50 mm)
distance lens-object 916 mm
distance ref.-object (top) 6 mm
distance ref.-object (bottom) 4 mm
reference 22.91 mm

Test specimen:
Thickness 30 mm
Notch 90 mm

Note:
The top reference is placed between the loadcell and the wedge.
WOLJ

Testing machine: WFW-Polymer Zwick 10 kN 0.5 mm/min
Maximum applied force: 417.5 N
Tforce2force: 0.03 sec
Tframe2frame: 0.2219 sec

Hentchel system:
cam 2
window 1.4 %
nmarc 26
fsam 937.5 Hz
transfr 8
llim 0
rlim 4095
step 12
camera lens 100 mm (2x50 mm)
distance lens-object 908 mm
distance ref.-object (top) 5 mm
distance ref.-object (bottom) 2 mm
reference 22.91 mm

Test specimen:
Thickness 30 mm
Notch 90 mm

Note:
The top reference is placed between the loadcell and the wedge.
WOLK

Testing machine: WFW-Polymer Zwick 10 kN 0.5 mm/min
Maximum applied force: 387.8 N
Tforce2force: 0.03 sec
Tframe2frame: 0.2219 sec

Hentchel system:
cam 2
window 1.4 %
nmarc 26
fsam 937.5 Hz
transfr 8
lim 0
rlim 4095
step 12
camera lens 100 mm (2x50 mm)
distance lens-object 910 mm
distance ref.-object (top) 6 mm
distance ref.-object (bottom) 4 mm
reference 22.91 mm

Test specimen:
Thickness 30 mm
Notch 90 mm

Note:
The top reference is placed between the loadcell and the wedge.
BALKAN

Testing machine: WFW Zwick 5 kN 0.5 mm/min
Maximum applied force: 1504.5 N
Tforce2force: 0.02 sec
Tframe2frame: 0.2389 sec

Hentzel system:
cam 2
window 1.4 %
nmarc 56
fsam 937.5 Hz
transfr 4
lim 0
rlim 4095
step 12
camera lens 100 mm (2x50 mm)
distance lens-object 910 mm
distance ref.-object 14 mm
reference 30.22 mm

Note:
The test specimen was fractured in two steps. In the first
test no fracture occurred within the expected 72 seconds. In
the second test the test was repeated but the test started at
1000 N.
Appendix I-13

BALKB

Testing machine: WFW Zwick 5 kN 0.5 mm/min
Maximum applied force: 1202.0 N
Tforce2force: 0.02 sec
Tframe2frame: 0.0747 sec

Hentchel system:
cam 2
window 1.4 %
nmarc 70
fsam 3750 Hz
transfr 4
llim 0
rlim 4095
step 12
camera lens 100 mm (2x50 mm)
distance lens-object 910 mm
distance ref.-object 14 mm
reference 30.22 mm

Note:
The test specimen fractured before the Hentchel system was started.
BALKC

Testing machine: WFW Zwick 5 kN 0.5 mm/min
Maximum applied force: 1651.0 N
Tforce2frame: 0.02 sec
Tframe2frame: 0.1493 sec

Hentchel system:
cam  2
window  1.4 %
nmarc  70
fsam  3750 Hz
transfr  8
llim  0
rlim  4095
step  12
camera lens  100 mm (2x50 mm)
distance lens-object  910 mm
distance ref.-object  14 mm
reference  30.22 mm

Note:
The test specimen fractured at the same time the Hentchel system was started.