Adequate Measurement of Force, Displacement and Crack Initiation in Dynamic Fracture Mechanics Experiments

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Abstract. Fracture mechanics testing at dynamic loading conditions requires appropriate methods for the measurement of force and displacement. In some cases additional measurement techniques must be used to obtain further information like the time of crack initiation. Dedicated standard procedures for impact type dynamic fracture mechanics tests are not available. Several standards on quasistatic or elevated loading rate fracture mechanics testing provide some more general experimental guidelines and they often exclude impact conditions. Therefore, the first step of dynamic fracture mechanics investigations should always be to establish an appropriate and validated test method.

The present paper reports on results of dynamic fracture mechanics investigations on bend type specimens. Series of large scale full blow bending tests on SE(B)140 specimens were performed at -40 °C and stress intensity rates of $5{\cdot}10^4$ MPa$\sqrt{\text{m}}$s^{-1}. Furthermore, series of small scale low blow tests on SE(B)25 specimens at room temperature as well as -40 °C and stress intensity rates of $2{\cdot}10^5$ MPa$\sqrt{\text{m}}$s^{-1} were run. The focus of this paper is on basic aspects of the experimental methods of such tests. The fracture mechanics characteristics of the materials in dependence on microstructural and loading parameters will be reported elsewhere.

The large scale full blow tests on SE(B)140 specimens were performed using a servo-hydraulic test system to determine dynamic fracture toughness values. Different strain gage instrumentations including the recommended ones of the standards were compared with respect to their force measurement capability. The deflection was measured using an electro-optical camera. A setup of two crack propagation sensors was glued to the ligament of the specimens in order to detect unstable crack initiation based on the crack speed measured. An appropriate method of instrumentation and measurement was identified whose results show good agreement with numerical simulations of the tests.

The low blow tests on SE(B)25 specimens were performed using a drop tower in order to determine dynamic crack resistance curves. It was shown in a series of comparison tests that strain gage instrumentations on the specimens for direct force measurement according to ASTM and BS provide different results. ASTM positions should be preferred. First choice for displacement measurement is using an electro-optical camera. This has been validated by different methods. The detection of stable crack initiation indicated by the first broken strand of a crack propagation sensor attached to the ligament right in front of the crack tip seems to be problematic when the specimen exhibits significant plastic behaviour. Current investigations aim on further improvement of the method.

It can be concluded that the recommendations of the test standards may provide different results. Therefore, they cannot simply be transferred to the own specific experimental tasks. It is absolutely

essential that the measuring techniques used are always being validated in advance with respect to own specific test requirements.

Introduction

Design and assessment of components subjected to high strain rate or impact (dynamic) loading require adequate material data. The focus of this paper is on the experimental determination of dynamic fracture mechanics material data which become essential when real or postulated cracks are taken into account. The problem of how to measure basic quantities in dynamic fracture mechanics tests like force and displacement correctly and with sufficient precision has still been an experimental challenge. Advice given on that by fracture mechanics standards such as BS 7448-3 [1] or ASTM E 1820 [2] is limited. The ISO standard 26843 [3] on the determination of dynamic fracture toughness using precracked Charpy specimens (PCVN) is still being drafted while comparable contents is already included in the very new annex 17 of [2].

A major lesson to be learned from experience is that the first step of experimental dynamic fracture mechanics investigations should always be to establish an appropriate test method. As will be shown below, transferability of measuring techniques from one lab to another, from small to large scale tests or vice versa and of more or less common advice from standards to the own very special task cannot simply be taken for granted. In contrary, it is of vital importance to validate the basic measured quantities independently before using the data for further analyses and to establish material characteristics. Basically this should be a matter of course. But studying the literature often reveals the opposite.

Usually, conventional techniques as machine load cells and clip-on transducers cannot be applied to measure the true mechanical response of the specimen due to the short duration of dynamic fracture mechanics tests (microseconds up to milliseconds), inertial effects and resulting signal oscillations. The information which is given on that by [1,2] is shortly summarized in Table1. Table 1 is limited to single edge bend specimens (SE(B)) since this type of specimen is primarily tested under dynamic loading at BAM. Table 1 outlines the starting point for a user when dynamic fracture mechanics tests are drafted. The first thing to note about Tab. 1 is that the recommendations of [1] and [2] regarding strain gage positions for force measurement are very different. This mirrors to some extent the status in the literature including for instance early basic studies of Ireland [4,5] or Trudeau [6] which are still frequently cited. Some own experimental results will be discussed below.

With respect to load line displacement measurement BS [1] does not provide a convenient method for higher loading rates. The recommendation to approximate the test machine ram displacement is rated not sufficient. Compared with this, ASTM [2] indicates that non-contact optical methods are suited and inertial effects shall be avoided.

Experimental investigations

The present paper reports on experimental fracture mechanics impact investigations on bend type specimens. Large scale full blow tests on SE(B)140 specimens as well as small scale low blow tests on SE(B)25 specimens were performed and experimental aspects of the test method are discussed here. The fracture mechanics characteristics of the materials are not in the focus of this paper and will be reported elsewhere.

Large scale full blow tests on SE(B)140 specimens. Series of large scale full blow tests on SE(B)140 specimens (length 1350 mm, width 280 mm, thickness 140 mm, $a_0/W = 0{,}5$) were performed at -40 °C by use of a servo-hydraulic impuls loading test system (max. 1 MN and 8 ms^{-1}) in order to determine dynamic fracture toughness values. Different strain gage instrumentations (Fig. 1) including as per BS and ASTM were compared with respect to their force measurement capability with SE(B)140 specimens at a stress intensity rate of $5{\cdot}10^4$ MPa$\sqrt{m}$s^{-1}. All strain gages were statically calibrated before the tests. Further details are reported for instance in [7].

Table 1. Standard information on force and displacement measurement in dynamic fracture mechanics tests on SE(B) specimens with $1 \leq B/W \leq 4$

<table>
<tr><th rowspan="2">Information on</th><th colspan="2">BS 7448-3 [1]</th><th colspan="3">ASTM E 1820 [2]</th></tr>
<tr><th>Main body</th><th>Annex A</th><th>Annex A13</th><th>Annex A14</th><th>Annex A17</th></tr>
<tr><td>loading rate</td><td>$3 < \dot{K} < 3000$ MPa√m/s</td><td>$\dot{K} > 3000$ MPa√m/s</td><td>$\dot{K} > 2{,}75$ MPa√m/s, not for impact or quasi-impact testing (free-falling or swinging masses), minimum loading time 1 ms</td><td>$\dot{K} > 2{,}75$ MPa√m/s, minimum test time to be calculated to avoid presence of a significant kinetic energy component in the specimen relative to the internal energy and to assure applicability of static J-integral equations</td><td>no restriction on impact velocity provided the time to fracture is greater than the calculated minimum test time</td></tr>
<tr><td>force measurement</td><td>machine load cell</td><td>resistance strain gages attached to both sides of the specimen, wired as two quarter bridges, positions: W/2 from ligament and at W/2 in width</td><td>machine load cell as used for static plane strain fracture toughness test generally suitable, but response characteristic to be checked to avoid inertial effects</td><td>on-specimen force measurement recommended (remote load cells allowed if requirements are met), full bridge of 4 strain gages on the specimen mid-plane at the specimen span quarter points (on upper and lower specimen side)</td><td>strain gage instrumented striker</td></tr>
<tr><td>displacement measurement</td><td>direct load line displacement via horizontal comparator bar</td><td>approximation by test machine ram displacement</td><td rowspan="2">same transducers as used for static plane strain fracture toughness test generally suitable, but response characteristic to be checked to avoid inertial effects</td><td>fibre-optic transducers</td><td>calculation from force/time record, no measurement</td></tr>
<tr><td>COD measurement</td><td>clip gage</td><td>-</td><td>cantilever beam displacement gages like in static fracture toughness testing down to loading times of 1 ms</td><td>-</td></tr>
</table>

Fig. 2 displays an example of force–time records and crack sensor signals. The test can roughly be assorted into 3 phases. During phase I, the rubber mat between striker and specimen is compressed and finally cut. After that, in phase II, the actual loading of the specimen takes place at a significantly higher but nearly constant loading rate compared to phase I. The stress intensity rate which is characteristic for the test is calculated as differential quotient in phase II.

Phase III is characterized by unstable cleavage crack growth until final fracture of the specimen. In phase III, the force signals F1–F4 and F2–F3 are not considered for further analysis with respect to the underlying test goal to determine dynamic fracture toughness at initiation of unstable cleavage fracture. The good agreement of the signals F1–F4 and F2–F3 illustrates the high symmetry of loading. As expected, the machine load cell only provides a damped and less sensitive force signal which is delayed in time.

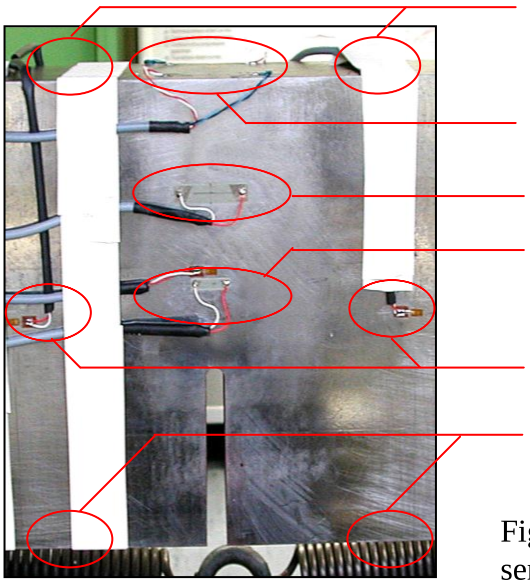

Fig. 1. Strain gage instrumentation and crack initiation sensors in and near the ligament of a SE(B)140 specimen.

Finite element simulations of the SE(B)140 impact tests in [8] showed a good agreement between time dependent F1–F4 and F2–F3 force signals and numerically determined force-time data. The calculated crack tip loading in terms of K at the experimentally provided time of cleavage crack initiation corresponds very well to the experimental K_{Id} value.

Common feature of all test series is that the ASTM strain gage positions F1-F4 and F2-F3 show smallest dynamic effects, best sensitivity and reproducibility up to unstable crack initiation. Fig. 3 shows examples of the responses of different ASTM as well as BS force strain gage instrumentations for several specimens. As Fig. 3a reveals, the signals of ASTM and BS strain gage positions may nearly coincide. But in most of the cases the BS signals are below ASTM and show much more dynamic effects, Figs. 3b and 3c. Mostly, the ASTM half bridges F1-F4 and F2-F3 provide comparable signals to the ASTM full bridge FO1-FO2-FU1-FU2 up to unstable crack initiation. Nevertheless, the F1-F4 and F2-F3 signals show slight advantages in reproducibility and very important - they offer valuable redundancy of measurement and simultaneously information on loading symmetry. The F1-F4 and F2-F3 signals do not instantly show sharp drops at unstable crack initiation as it is known from Type I, II or III brittle behaviour of small PCVN specimens as per Annex 17 of [2] but keep rising until the crack has reached the crack sensor in the ligament, Fig. 2. This is not of concern when stable crack growth is absent and the test is only analyzed until unstable crack initiation. Nevertheless, this underlines the necessity of an adequate experimental method for detection of unstable crack initiation.

Here, a method was used where the initiation of unstable cleavage crack extension is indicated by fracture of the first strand of a crack sensor (Fig. 1) close to the crack tip (steep signal rise in Fig. 2). However, since this crack sensor is not positioned at the crack tip directly but some millimeters in front of, a correction of the initiation time has to be made. This is done by means of the crack velocity which is calculated from the known distance between the crack sensors and the time measured between their responses. Since the distance between the crack tip and the first crack sensor is known too, the corrected time of unstable cleavage crack initiation can then be calculated. Due to the very limited plasticity in the ligament no problems related to sensors stripping away from the specimens surface were observed.

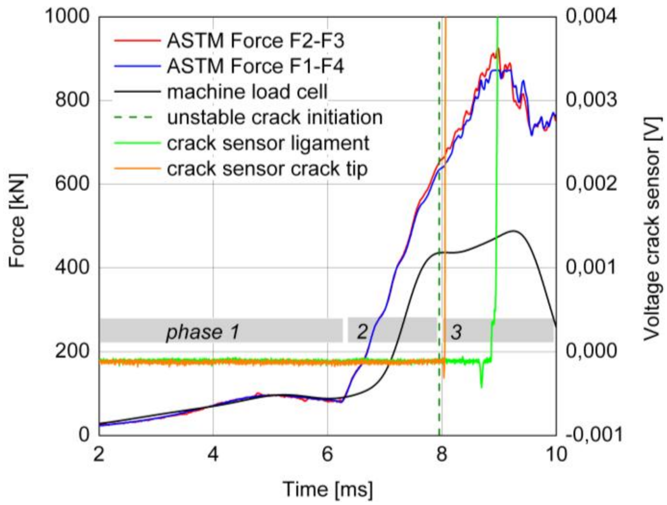

Fig. 2. Examples of signals from a dynamic SE(B)140 fracture mechanics test.

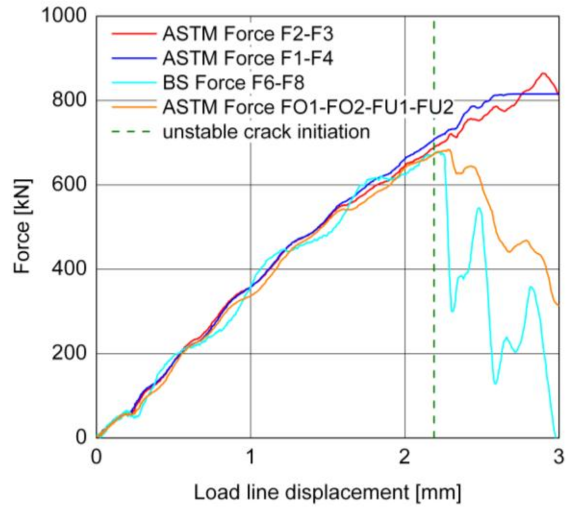

Fig. 3a. Examples of force-displacement records of dynamic SE(B)140 fracture mechanics tests.

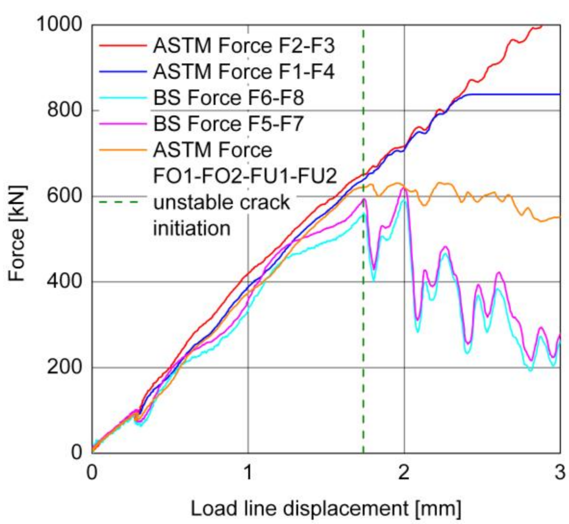

Fig. 3b. Examples of force-displacement records of dynamic SE(B)140 fracture mechanics tests.

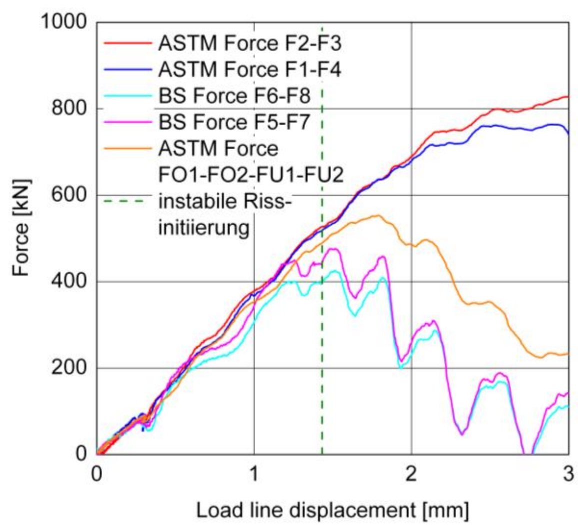

Fig. 3c. Examples of force-displacement records of dynamic SE(B)140 fracture mechanics tests.

Since tactile displacement measurement devices are much too slow, the load line displacement was measured using an electro-optical camera, Fig. 4. The camera has two objective lenses each of which tracing a black-white contrast on the specimen ligament so that two redundant displacement signals can be provided. The camera measurement technique is validated statically by gauge blocks and dynamically by comparison of results of elongation measurement at rupture in dynamic tensile tests with the corresponding manually determined values.

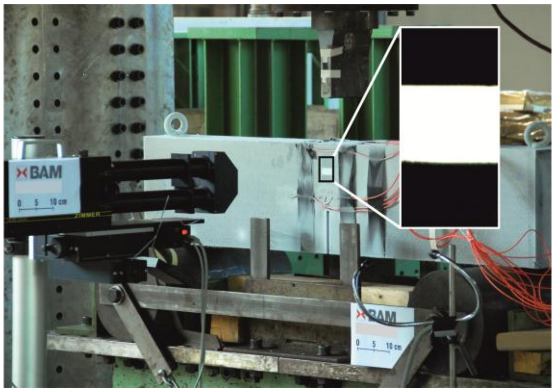

Fig. 4. Electro-optical camera for measurement of load line displacement in dynamic SE(B)140 specimen tests.

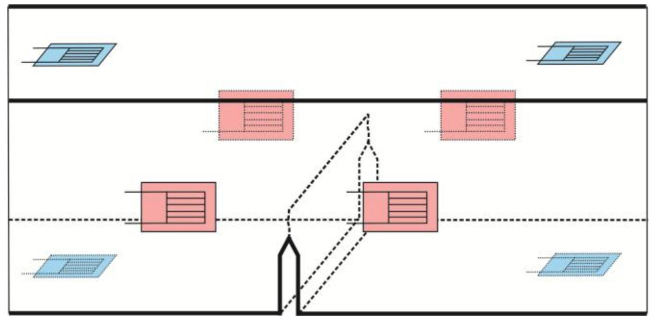

Fig. 5. Strain gage instrumentations for direct force measurement on SE(B)25 specimens, blue: ASTM full bridge at specimen quarter points, red: 2 BS half bridges at W/2.

Small scale low blow tests on SE(B)25 specimens. Series of small scale low blow tests on SE(B)25 specimens (length 138 mm, width 25 mm, thickness 25 mm, a_0/W = 0,5) were performed at room temperature by use of a drop tower test system (stress intensity rate in the linear-elastic range approximately $2{\cdot}10^5$ MPa$\sqrt{\text{m}}$s^{-1}). Primary goal was to setup a multiple specimen test method to determine dynamic crack resistance curves. Again, different strain gage instrumentations (Fig. 5) were compared with respect to their force measurement capability. All strain gages were statically calibrated before the tests.
It was shown that strain gage instrumentations according to ASTM and BS provide different results independent from temperature, Fig. 6. To clarify this, reference tests under quasistatic loading had been performed with the same instrumentation, Fig. 7. They revealed that the ASTM signal widely conforms to the reference while BS significantly differs and displays a remaining tensile force at the end of the test when the specimen is fully unloaded. In order to investigate if plasticity at the

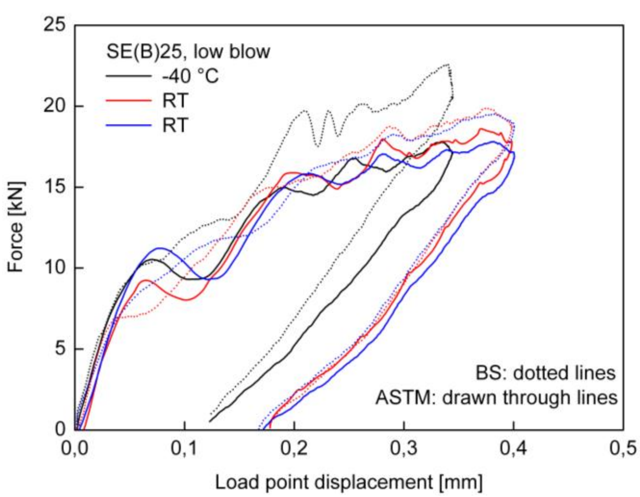

Fig. 6. Comparison of ASTM and BS strain gage force measurement on SE(B)25 specimens in low blow tests.

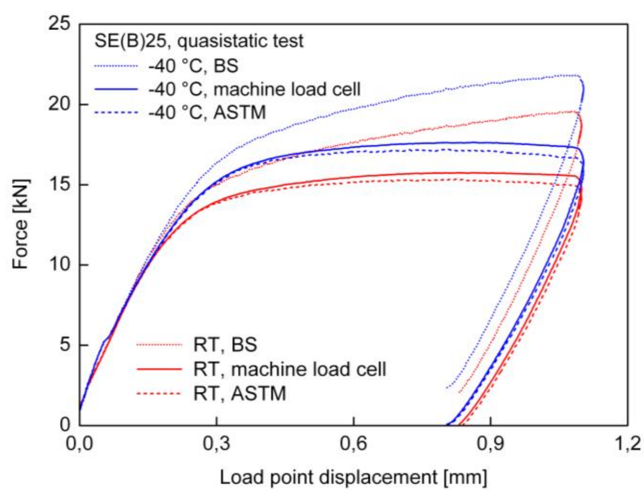

Fig. 7. Comparison of ASTM and BS strain gage force measurement on SE(B)25 specimens in quasistatic tests.

BS W/2 positions causes these differences (note: W = B and not W = 2B), a test with BS strain gages at a distance of W from the ligament was performed. A significant improvement could not be achieved. Therefore it is concluded for low blow tests that strain gages at ASTM positions work well with the investigated SE(B)25 specimens while BS positions cannot be recommended.

Basically, the load line displacement for tests in instrumented pendulum impact machines or drop towers can be determined by double integration of the force-time record. This is considered an attractive way to provide displacement data when expensive non-contact measuring equipment is not available or not applicable. However, as can be seen from Fig. 8, tremendous differences/errors may occur between the calculated values and the reference measured by an independent and verified method. The errors were due to slight energy losses by hidden friction which may easily occur

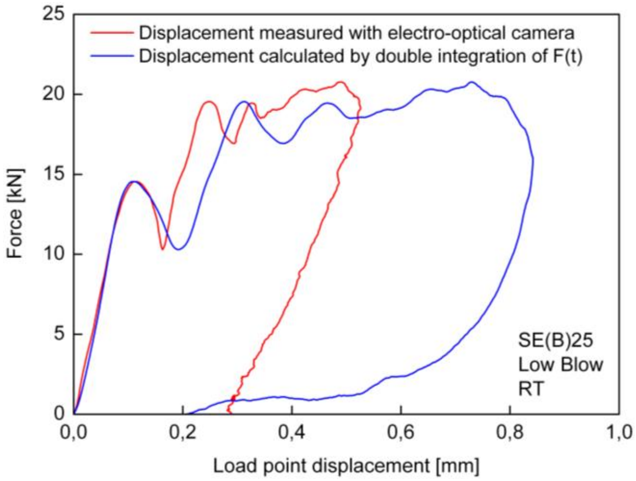

Fig. 8. Force vs. calculated and measured displacement, drop tower with friction losses.

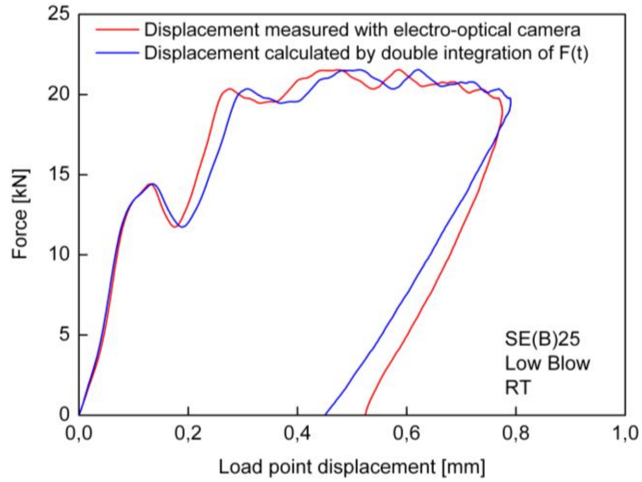

Fig. 9. Force vs. calculated and measured displacement, optimized drop tower.

especially in larger drop towers. Therefore, the drop tower was constructively optimized and the tests were repeated, Fig. 9. The calculated and the measured displacement values are nearly equal now so that dynamic fracture mechanics tests could even be performed without having special equipment for displacement measurement available. But it must be considered an absolute essential prerequisite that this procedure can only be followed when the substance of Fig. 9 had been proven in advance.

The experimental detection of stable crack initiation in dynamic tests has still not yet been resolved satisfyingly. Reported techniques like magnetic emission, acoustic emission or near crack tip strain gages seem to work in special cases but cannot be seen as robust methods or generally be applicable. Therefore, the detection of stable crack initiation by the first broken strand of a crack propagation sensor attached to the ligament right in front of the crack tip was investigated here, Figs. 10 and 11. It was observed that the crack sensors provide discrete signal jumps in quasistatic and dynamic tests on SE(B)25 specimens at RT and -40 °C. Nevertheless, there is a large scatter of detected initiation forces F_{ini} of $0,5F_{max} \leq F_{ini} \leq 1,0F_{max}$. In contrary to the SE(B)140 tests, partial sensor detachment in the plastic zone surrounding the crack was observed so that the method cannot yet be seen as reproducible with SE(B)25. Current investigations aim at the influence of material plasticity in the specimen below the crack sensor and a correction of F_{ini} by consideration of the real initial crack length.

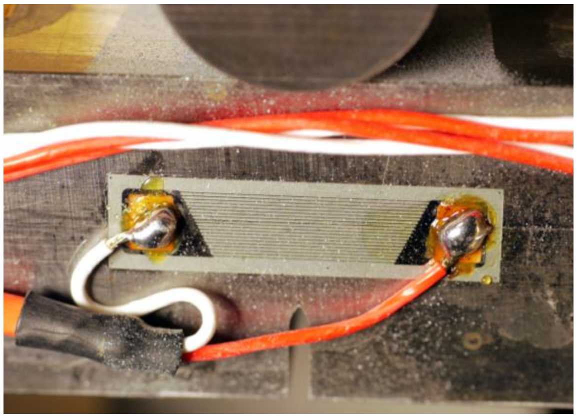

Fig. 10. Crack sensor at the crack tip of a SE(B)25 specimen.

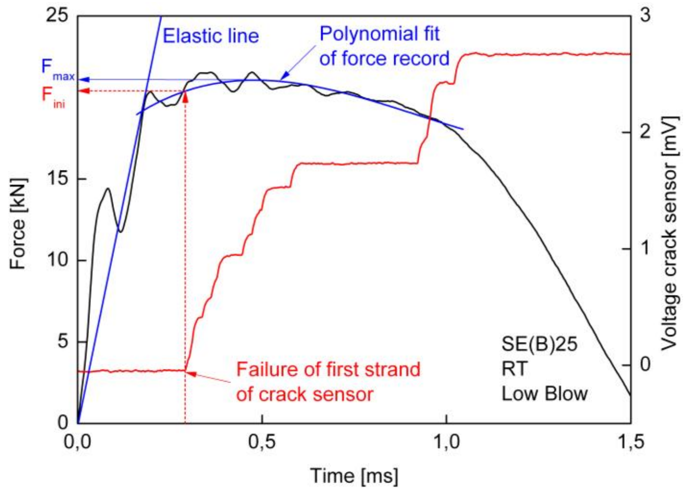

Fig. 11. Principle of detection of stable crack initiation by failure of crack sensors.

Summary
Different techniques for the measurement of force, displacement and crack initiation in dynamic fracture mechanics tests on SE(B)140 and SE(B)25 specimens were investigated. It can be concluded that the fairly limited recommendations of the test standards may provide different results. Therefore, they cannot simply be transferred to the own specific experimental tasks. It must be considered an absolute essential prerequisite that the used measuring techniques are validated in advance. The detection of unstable crack initiation by crack sensors in K_{Id} tests works well. Compared to that, the use of crack sensors to detect stable crack initiation in low blow R-curve tests needs further investigations.

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