FRACTURE TOUGHNESS OF
FAST PROPAGATING CRACKS IN ROCK

A. Bertram and J.F. Kalthoff
Experimental Mechanics, Ruhr-University Bochum, 44780 Bochum, Germany

ABSTRACT

A fracture mechanics characterization is performed of mode-I crack propagation processes in natural rock. High levels of crack propagation velocity are generated in Solnhofen limestone by providing high levels of elastic energy at the tip of the initial notch at the moment of initiation. This is experimentally achieved by subjecting the initial notch to impact loading conditions and/or by initiating the tensile (mode-I) crack from a shear (mode-II) loaded starter notch. The dynamic stress intensity factors and the velocity of the propagating cracks are measured by a chain of strain gauges positioned along the prospective crack propagation path. The strain gauge measuring technique is used in an optimized form to reduce the influence of higher order terms of the crack tip stress field. Cracks are accelerated to velocities up to about 2000 m/s. The measured crack propagation toughnesses are significantly (almost a factor of ten) higher than the crack initiation toughness. Thus, the energy dissipated by a crack propagating at a high velocity is almost two orders of magnitude larger than the energy to initiate a crack. Furthermore, the data do not only show a sharp increase of the fracture toughness in the regime of high crack propagation velocities but also in the regime of very low velocities. The fracture toughness crack velocity dependence shows an R-curve type behaviour as typically found for ductile steels. The results explain characteristic peculiarities of the crack propagation behaviour of brittle fracture in rock.

1 INTRODUCTION

In geology deformations of the upper crust of the earth predominantly result from fracture processes and dislocations at preexisting faults in response to tectonic loading. An understanding and a quantitative description of such crack propagation processes requires knowledge on the energetic conditions that control the fracture processes, i.e. on the toughness of the rock materials, not only for initiation but in particular also for the various phases of crack propagation that are characterized by different velocities. Standardized procedures are available for determining the crack initiation toughness K_{Ic}. Procedures for determining the equivalent property for propagating cracks are only used in research oriented work, and, as a consequence, only limited data are available in the literature [1,2,3]. Fracture toughnesses have frequently been measured for rocks of various types [4], but predominantly in the form of crack initiation toughnesses K_{Ic}; only a limited number of publications exist on the dynamic fracture behaviour of rock [5]. In this study the fracture toughness of cracks propagating under tensile (mode-I) conditions is measured over a large range of velocities from low to very high crack propagation speeds (see also [6]).

2 BACKGROUND

Crack propagation toughnesses are measured in form of the quantity K_{ID}, i.e. the critical stress intensity factor K at a specific crack propagation velocity v. In general, when considering the typical behaviour observed with some structural materials, K_{ID} as a function of crack propagation velocity v is given by a curve as shown in Fig. 1: In the low velocity range, K_{ID} decreases with increasing crack propagation velocity due to strain rate effects; in the high velocity range K_{ID} increases with increasing crack propagation velocity due to rising temperatures at the crack tip and a reduction in the degree of multiaxiality of the crack tip stress field. The crack propagation velocity is limited by the terminal velocity v_{max}, theoretically given by the Rayleigh wave speed, in

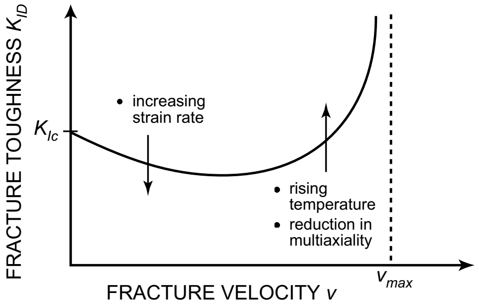

Figure 1: Fracture toughness as a function of crack propagation velocity, schematically.

practice by a much lower value. At the terminal velocity the fracture toughnesses assume very high values. With materials that fail in a brittle manner showing no or only little ductility, the effect of embrittlement is very low and the initial slope of the curve is almost horizontal [7].

3 TEST METHODOLOGY

Dynamic crack propagation toughnesses are measured with a brittle rock, Solnhofen limestone. This rock type is very homogeneous (monomineralic - 99% calcite, micritic - grain size < 5 μm). Typical values of the fracture toughness and the tensile strength are $K_{Ic} = 0.8 \cdots 1$ MN/m$^{3/2}$ and $\sigma_t \approx 20$ MPa, thus, relatively small process zones result for this material, which guarantee a reliable application of the conventional concept of linear elastic fracture mechanics.

Brittle fracture in rock shows a peculiarity: Pretests have been performed to accelerate a crack to high velocities utilizing two materials, the model material Araldite B, an epoxy resin, with a strongly linear elastic material behaviour failing in a brittle manner, and, the rock material under consideration, Solnhofen limestone. Three-point-bend tests were performed under quasistatic loading using fully identical test conditions as regards specimen size, length of the initial crack, notch tip acuity, etc. As shown in Fig. 2, the crack in the model material epoxy resin accelerates rapidly to its terminal crack velocity (indicated by immediate crack branching), whereas the crack in Solnhofen limestone exhibits a much lower velocity even after a much longer crack propagation path, not reaching the terminal velocity at all. Obviously, in contrast to conventional brittle materials, the energy to propagate a crack in brittle rock must be significantly higher than the crack initiation energy, so that large propagation distances are necessary to accumulate stress intensities large enough to meet the conditions for high crack propagation velocities.

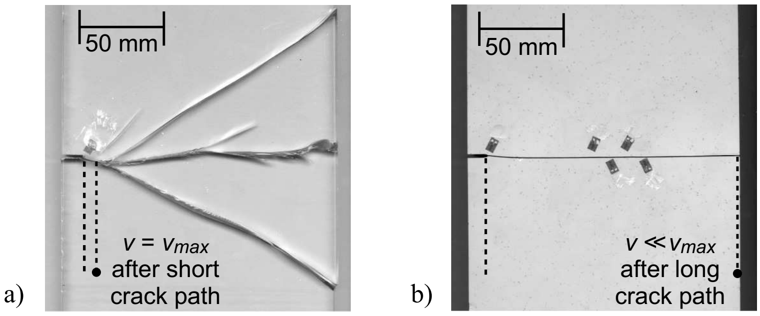

Figure 2: Behaviour of crack propagation in: epoxy resin Araldite B (a), Solnhofen limestone (b).

In order to achieve high crack propagation velocities in Solnhofen limestone in laboratory test specimens with limited crack propagation paths two techniques are applied: Firstly, impact loading of the specimens is used to generate surplus energy conditions for the crack propagation process; three-point-bend specimens are impacted by a drop weight tower. Secondly, tensile (mode-I) crack propagation is initiated from a starter crack loaded under shear (mode-II) conditions since previous investigations [8] have shown that the crack tip energy at the moment of instability of a mode-II loaded starter crack is larger than for the situation of a mode-I loaded crack. The kinked mode-I crack that is initiated from such a mode-II loaded starter crack, thus, experiences larger energies in comparison to the equivalent mode-I loading case, and, consequently, can accelerate to higher velocities within shorter distances. The technique of mode-II loading and the technique of impact loading are combined to a technique generating impact shear conditions of loading. The technique of loading edge cracks by edge impact (LECEI-technique) is used for this purpose (see Fig. 3, [9]): A specimen with an edge crack or an edge notch is asymmetrically impacted (above the crack in direction of the crack). The impinging impactor initiates a compressive wave in the upper part of the specimen, causing a mode-II loading condition at the tip of the crack or the notch. The resulting stress intensification rates are extremely high [9]. Data are reported that are obtained by the one or the other technique for achieving high crack propagation velocities. In addition, quasistatic conditions of loading of three-point-bend specimens are utilized for achieving low crack propagation velocities, when considered necessary.

The crack propagation toughness, i.e. the value of the stress intensity factor at a particular crack propagation velocity, is measured by means of a strain gauge technique: A chain of strain gauges is mounted on the specimen along the prospective crack propagation path [10]. The position of the strain gauge (SG) with respect to the position of the momentary crack tip is characterized by the polar angle φ, the measuring direction α and the distance r (see Fig. 4a). The distance r of the strain gauge to the crack tip must be kept sufficiently large to ensure that influences of the crack tip process zone are limited; on the other hand, the influence of higher order terms of the crack tip stress field increases for larger crack tip distances. The stress intensity factor K can nevertheless be determined from the strain gauge signals ε_{SG} with a sufficiently high accuracy by choosing the angular positions φ and α of the strain gauges in such a way that the influence of the higher order terms of the crack tip stress field is eliminated or at least minimized, this is the case for $\varphi_{opt} = 65^\circ$ and $\alpha_{opt} = 61^\circ$ [11]. For propagating cracks, the crack passes by the strain gauges and characteristic load signals result as given in Fig. 4b (schematically shown for two strain gauges SG1 and SG2). The stress intensity factor is then determined from the maximum value of the strain measured as a function of time, furthermore, the crack propagation velocity is estimated from the time shift of the two signals and the distance of the two strain gauges.

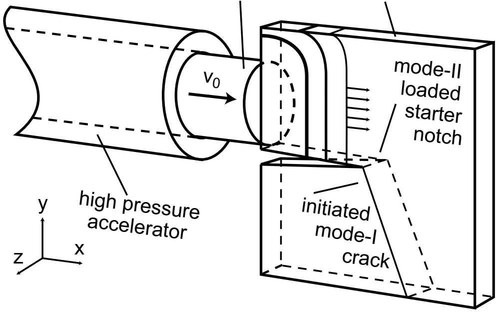

Figure 3: Initiation of fast crack propagation by asymmetric edge impact of an edge crack.

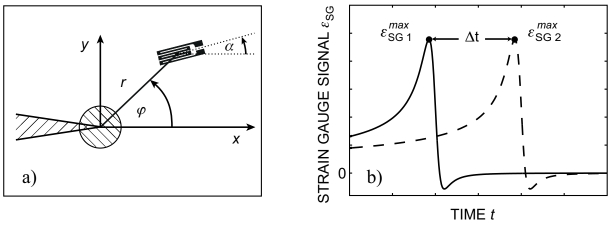

Figure 4: Strain gauge technique for measuring stress intensity factors: a) strain gauge location, b) strain gauge signals for propagating crack.

4 EXPERIMENTAL RESULTS

Single-edge-notch-bend (SENB) specimens measuring 550×200×20 mm are used in three-point-bend tests. The length a_0 and the acuity ρ of the starter notch is varied ($a_0 = 2 \cdots 80$ mm, $\rho = 0.125 \cdots 0.75$ mm). These parameters allow for further control of the crack speed. Specimens measuring 200×200×20 mm ($a_0 = 100$ mm, $\rho = 0.5 \cdots 1$ mm) are used for the LECEI tests. In all cases, a chain of strain gauges is mounted on the specimen along the prospective fracture path. In addition, a strain gauge is positioned near the tip of the starter notch for monitoring the conditions at initiation of the failure event. The SENB-specimens are quasistatically loaded in a servo-hydraulic test machine at a cross head speed of 10^{-6} m/s, or the specimens are impact loaded in a drop weight tower at about 1 m/s. In the LECEI-tests velocities in the range of 10 to 25 m/s were utilized for impacting the specimen. Typical data for these three types of tests are given in Fig. 5. An evaluation of these data on the basis as described before yields the following results:

Maximum crack propagation velocities up to the range of about 2000 m/s (see concluding Fig. 7) are obtained. Figure 6 shows high speed recordings of the propagation of a kinked mode-I crack initiated from a mode-II loaded starter notch by means of the LECEI-technique. Crack branching is observed in this experiment indicating that velocities in the range of the terminal crack velocity are indeed obtained. These very high crack velocities demonstrate the suitability of the technique of impact and/or mode-II loading to achieve fast fracture propagation events.

An evaluation of all the tests performed result in fracture toughness K_{ID} as a function of crack speed v, as given in Fig. 7. The toughnesses measured over the entire range of crack velocities vary to a large extent: At very high propagation velocities, approaching the terminal velocity, a strong increase of the fracture toughnesses is observed with increasing crack propagation velocity - as is expected. But, another strong increase of the fracture toughness is observed directly after the

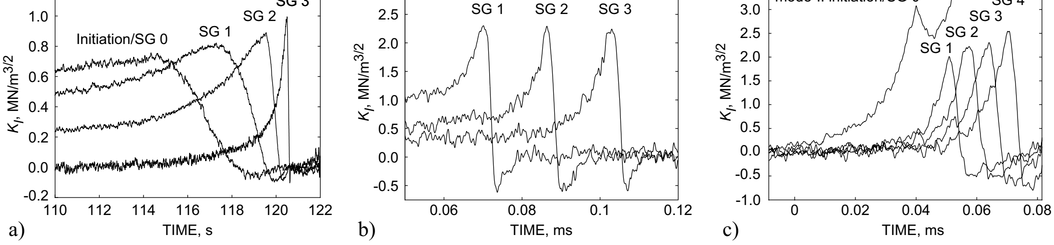

Figure 5: Typical strain gauge signals: a) for accelerating crack at low velocities (quasistatic mode-I loading), b) for fast propagating crack (impact mode-I loading), and c) for fast propagating crack (impact mode-II loading).

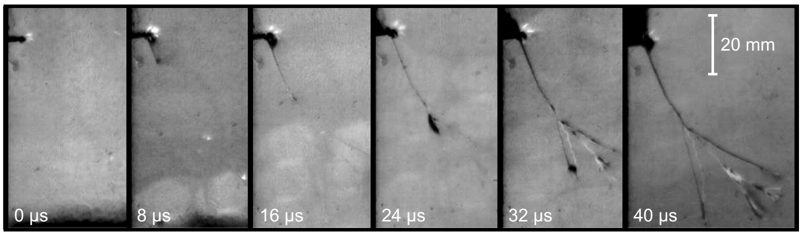

Figure 6: High speed photographs of crack propagating event in Solnhofen limestone.

onset of crack growth, i.e. at low crack propagation velocities. The lowest toughnesses shown in Fig. 7 represent initiation toughnesses which are plotted at zero velocities in the figure. These toughnesses were determined with blunted starter cracks of finite radii ($\rho = 0.125 \cdots 1$ mm) resulting in apparent toughnesses (K_{Ic}^* or K_{Id}^*, for the cases of quasistatic or impact loading respectively) which are higher than the toughnesses of equivalent sharp initial cracks. The lowest values in Fig. 7, consequently, would have to be corrected to even lower values to reflect the situation for equivalent true initiation fracture toughnesses. Thus, from initiation to velocities of 2000 m/s the fracture toughness is found to increase by almost an order of magnitude.

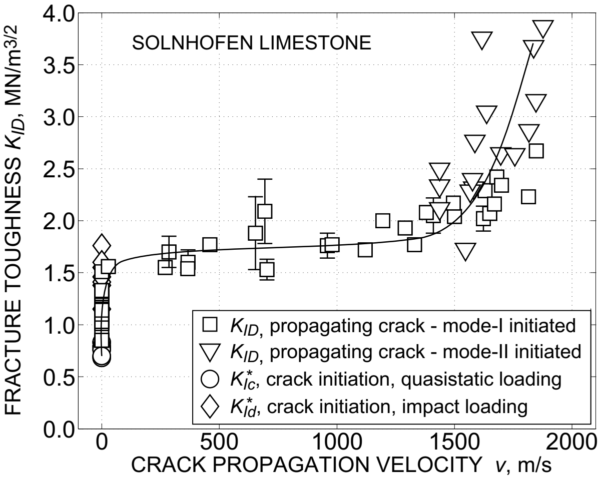

Figure 7: Fracture toughness of propagating cracks in Solnhofen limestone.

5 CONLUSIONS

Crack propagation toughnesses K_{ID} have been measured in Solnhofen limestone over a large range of crack propagation velocities from the onset of crack propagation up to velocities in the range of 2000 m/s. The toughness-velocity-curve shows two regimes where the toughness increases very steeply with crack velocity: not only at very high velocities - as it is expected - but also at low velocities directly after onset of crack propagation. The behaviour observed at low velocities exhibits an R-curve character, i.e. a behaviour as is typically observed with structural materials showing ductile behaviour although Solnhofen limestone is considered a brittle material. The strong increase of the fracture toughness at these low crack velocities explains the peculiar crack propagation behaviour in rock: Large propagation distances are necessary in order that the crack can accumulate sufficiently high stress intensity factors to balance the large crack propagation toughnesses that apply for high crack velocities. Furthermore, the occurrence of stable, subcritical crack growth associated with an R-curve type fracture behaviour is in agreement with the occurrence of the phenomenon of controlled crack growth in brittle rock with stiff quasistatic test devices [12]. The high toughnesses of propagating cracks in comparison to the toughness at crack initiation result in energy dissipations of propagating cracks being almost two orders of magnitude larger than for crack initiation. On the basis of this results the accuracy of energy balance considerations of earthquakes can be improved: These energy balance estimates usually use quasistatic crack initiation data, but fracture processes in earthquake events are typically dynamic processes occurring at high crack propagation velocities for which the actual energy consumption is considerably higher than for onset of crack propagation, as shown by the investigations reported.

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