# DETERMINATION OF THE DYNAMIC FRACTURE TOUGHNESS $K_{Id}$ IN IMPACT TESTS BY MEANS OF RESPONSE CURVES

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## ABSTRACT

A procedure is presented for determining the impact fracture toughness $K_{Id}$ of structural steels without performing a load measurement at the striking hammer. The elastic response of the specimen to the impact process, i.e. the dynamic stress intensity factor versus time curve, $K_I^{dyn}(t)$, is determined in pre-experiments. The shadow optical method of caustics in reflection with an appropriate high strength steel is utilized for establishing this impact response curve. The dynamic fracture toughness for a given structural steel is then determined by performing an impact experiment and measuring the time to fracture $t_f$. $K_{Id}$ is obtained from the measured $t_f$-value and the pre-established impact response curve which corresponds to the experimental test conditions. The presented measuring procedure is used for determining the dynamic fracture toughness of two different steels at different test temperatures.

## KEYWORDS

Fracture dynamics, material properties, impact testing, dynamic fracture toughness, stress analysis, photoelasticity.

## INTRODUCTION

Instrumented impact tests are currently used to measure the dynamic fracture toughness $K_{Id}$ of materials. During the impact event, the load at the tup of the striking hammer is recorded as a function of time (or deflection of the specimen). From the critical load for onset of crack propagation the dynamic fracture toughness value $K_{Id}$ is derived utilizing the conventional static stress intensity factor formulas (ASTM STP 466, 1970; ASTM STP 563, 1974; IIW Commission, 1976; PVRC/MPC Joint Task Group, 1974).

Difficulties are inherent with this measuring and evaluation procedure: first, because the load time records oscillate and often cause uncertainties in the determination of the actual fracture load, and secondly, because a dynamic material strength value is inferred from a static evaluation analysis.

The conventional measuring technique therefore can only yield meaningful data if fracture occurs after times sufficiently large that a quasi static loading condition has been reached in the specimen. For shorter loading times to fracture dynamic effects can strongly influence the stress state in the specimen (Glover and co-workers, 1976; Kalthoff and co-workers, 1977a, 1979; Ireland, 1976; Loss and co-workers, 1975; Radon, 1969; Turner, 1970, 1975; Venzi and co-workers, 1975; Winkler and co-workers, 1979). If these dynamic influences on the measured load records are not taken into account, erroneous data can be obtained which may lead to an overestimation of the true toughness of the material (IIW Commission, 1976; Glover and co-workers, 1976; Matthews, 1970; Turner, 1970). It is postulated, therefore, (Ireland, 1970; PVRC/MPC Joint Task Group, 1974; Turner, 1975) that the quasi static procedure can be applied only when the time to fracture $t_f$ of the specimen is larger than about three times the period $\tau$ of the oscillation of the impacted specimen:

$$t_f > 3\,\tau \qquad (1)$$

The period $\tau$ is given approximately by the empirical formula (IIW Commission, 1976; Glover and co-workers, 1976; Matthews, 1970; Turner, 1970)

$$\tau = 1.68\,(S \cdot W \cdot B \cdot C \cdot E)^{1/2}/c_1 \qquad (2)$$

where S is the support span, W and B are the width and the thickness of the specimen, C is the specimen compliance, E is Young's modulus and $c_1$ is the longitudinal wave speed. Short periods, therefore, result for small specimen dimensions. Large fracture times, on the other hand, are obtained only when rather ductile materials are tested at low impact velocities. The condition (1) therefore restricts the applicability of impact tests in an unsatisfactory way:

- Specimens of large dimensions, which are often required for a valid toughness test, cannot be utilized.
- Materials which fail in a more brittle manner cannot be investigated.
- The maximum allowable loading rate is limited.

This paper presents a procedure for measuring the dynamic fracture toughness that does not have these restrictions. The procedure can be applied for all experimental test conditions, especially in the brittle fracture and high velocity impact range, as long as the usual conditions for small scale yielding are fulfilled.

## BASIC PRINCIPLE OF THE CONCEPT OF IMPACT RESPONSE

### Background

In previous investigations by some of the authors (Kalthoff and co-workers, 1977a, 1979a; Winkler and co-workers, 1979) the impact event was analyzed by performing experiments with prenotched bend specimens made from a model material and from steels. In addition to the load signal at the striking hammer, the dynamic stress intensity factor directly at the crack tip in the specimen was measured. In these experiments the gross test conditions were fixed, i.e. the same striking hammer, impact velocity, specimen material and geometry were used, but the specific conditions for crack initiation, namely the notch tip acuity or the toughness of the material, were varied. In all the experiments, one unique curve for the stress intensity factor as a function of time, $K_I^{dyn}(t)$, was found. The critical stress intensity factors for onset of crack propagation were discrete values along this curve corresponding to the different times at which fracture initiation took place. The existence of such a behavior was also considered by Loss (1975).

### Principle of the Measuring Methodology

Based on these experimental findings, a measuring procedure is proposed for determining the dynamic fracture toughness values $K_{Id}$ for structural steels. The mechanical response of the specimen during impact is determined in pre-experiments. Utilizing the shadow optical method of caustics in reflection with an appropriate high strength steel, the dynamic stress intensity factor is established as a function of time, $K_I^{dyn}(t)$. This curve is called impact response curve.

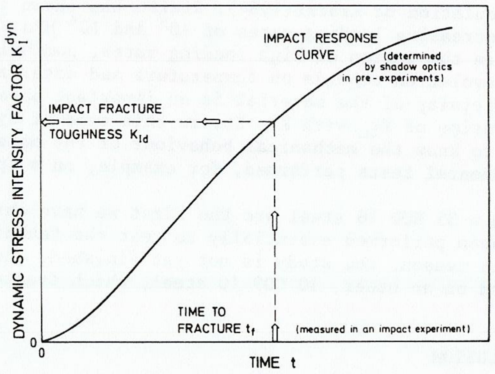

Fig. 1. Determination of the dynamic fracture toughness $K_{Id}$ by impact response curves (schematically)

The dynamic fracture toughness for a given structural steel is then determined by performing an impact experiment and measuring the resulting time to fracture. The dynamic fracture toughness value is obtained (see Fig. 1) from the pre-established impact response curve and the measured time to fracture $t_f$ by the relation

$$K_{Id} = K_I^{dyn}(t = t_f). \qquad (3)$$

The proposed procedure is described in more detail in the following sections. The determination of the impact response curve in general as well as the results obtained for one special experimental condition are presented. A technique for time to fracture measurements is developed. Finally the impact response concept is used to determine fracture toughness values for two different steels at several temperatures.

## DETERMINATION OF IMPACT RESPONSE CURVES

Stress intensity factors can be derived directly from the linear elastic stress strain field around the crack tip by means of the shadow optical method of caustics. This method, originally introduced by Manogg (1964) and later extended by Theocaris (1970), is an effective and simple experimental tool for determining stress intensity factors. It is particularly well suited for determining dynamic stress intensity factors when used in combination with high speed photography. The method has been successfully applied by Kalthoff and co-workers (1977a, 1977b, 1979, 1980) to dynamic fracture problems such as crack arrest and instability of cracks under impact and is used here for establishing the impact response curves.

### The Shadow Optical Method of Caustics

The physical principle of the shadow optical method of caustics applied in reflection is sketched in Fig. 2. The upper part of the figure (Fig. 2a) shows the experimental arrangement. The mirrored surface of a notched steel specimen under load is illuminated by a light beam. The specimen is photographed by a camera focussed on a virtual image plane located behind the specimen. A cross section through the specimen at the position of the crack tip is shown in Fig. 2b. Due to the stress intensification at the crack tip, the thickness of the specimen is reduced in the area surrounding the crack tip. As a consequence, light near the crack tip is deflected towards the center line. An extension of the reflected light beams onto the virtual image plane at a distance $z_o$ behind the specimen results in a light configuration showing the crack tip as a dark shadow spot

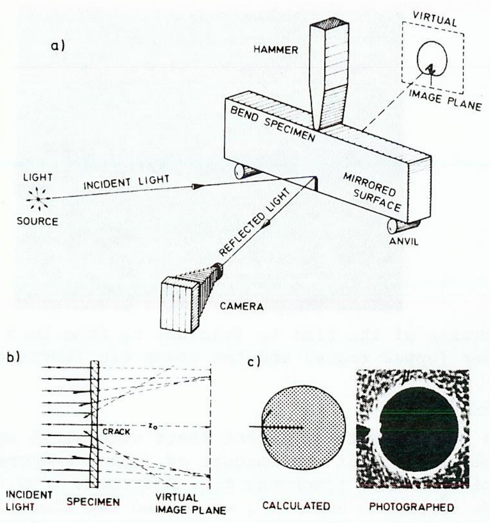

Fig. 2. The shadow optical method of caustics in reflection
a) Experimental set-up b) Light configuration c) Shadow pattern

bounded by a region of bright light (the caustic). The mode I shadow pattern was calculated by Manogg from the linear elastic stress strain field around the crack tip. Figure 2c compares the result with the shadow pattern from a high strength steel specimen.

Quantitatively the diameter D of the caustic is a function of the stress intensity factor $K_I$ and is given by

$$K_I = M \cdot D^{5/2} \tag{4}$$

$$\text{with } M = 9.34 \cdot 10^{-2} \, \frac{E}{\nu \, B \, z_o} \tag{5}$$

where D = Diameter of the caustic (for parallel light incident)
E = Elastic modulus
$\nu$ = Poisson's ratio
B = Thickness of the plate
$z_o$ = Distance between specimen and image plane

Further experimental details of the technique are given by Beinert and Kalthoff (1980).

## Experimental Procedure

In order to apply the method of shadow patterns to steel and to determine a stress intensity factor from the elastic stress-strain field in the vicinity of the tip of the crack, a steel with a sufficiently small plastic zone at the crack tip had to be utilized.

Bend specimens measuring 280 mm by 60 mm (10 mm thick) with initial notches of length $a_o$ = 20 mm were machined from the high strength maraging steel X 2 NiCoMo 18 9 5[1] heat treated to a yield strength of $\sigma_y$ = 2100 MN/m$^2$ and a crack initiation toughness $K_{Ic}$ of about 80 MN/m$^{3/2}$. The elastic modulus E and Poisson's ratio $\nu$ of this steel are about the same as those of usual structural steels. One side of the specimens was ground, lapped, and hand polished to achieve a highly planar and mirrored surface. The tip of the notch was blunted to increase the load carrying capacity of the specimen and thus allowed the impact response to be measured at stress intensity factors exceeding the fracture toughness of this steel. The specimens were tested on a support span of 240 mm in a DYNATUP 8100 drop weight tower. The mass of the striking hammer was 90 kg, the impact velocity was 5 m/s.

During the impact process shadow patterns at the tip of the crack were recorded with a Cranz Schardin 24 spark high speed camera. The distance $z_o$ between specimen and image plane was 1.5 m. The high speed camera was triggered by the sudden increase of the load signal registered by the strain gage on the hammer at the moment of contact with the specimen.

## Experimental Results

A series of shadow optical pictures of the central part of the specimen taken during the impact event is given in Fig. 3. Only 12 out of the total of 24 pictures are reproduced here. The time from the beginning of the impact process is indicated in each photograph.

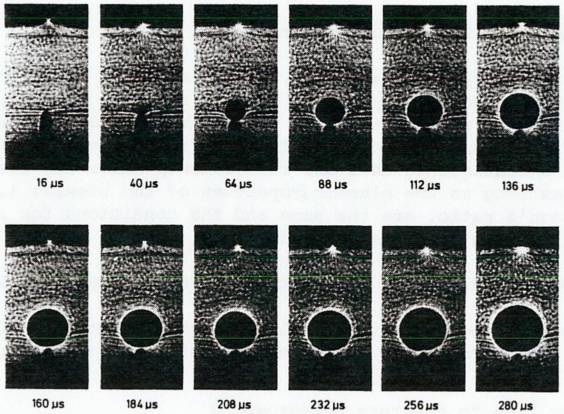

Fig. 3. Shadow optical photographs of the bend specimen during the impact event

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[1] Produced by Stahlwerke Südwestfalen and designated HFX 760.
Nominal composition: 18% Ni, 9% Co, 4.8% Mo and < 0.03% C.
Heat treatment: 480° C for 4 hrs in air. This steel is similar to the American designation 18 Ni maraging grade 300.

Stress intensity factors obtained from such photographs are presented in Fig. 4. Data from several experiments performed under identical conditions are reproduced for times to 280 μs after impact. The nonlinear increase of the dynamic stress intensity factor with time is caused by dynamic effects in the specimen.

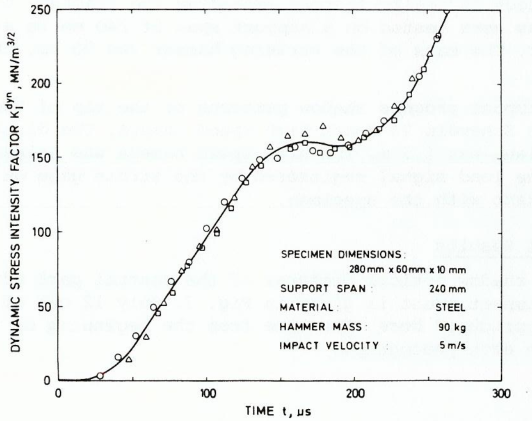

Fig. 4. Impact response curve

The $K_I^{dyn}(t)$-curve relates quantitatively the response of the specimen to the impact event. The curve depends only on the elastic reaction of the specimen-impactor system, and therefore, is unique for the system considered and applies to all steel specimens of same size tested under the same impact conditions. It is important to note that as a consequence this one relationship holds for steels of different toughnesses as long as the elastic properties of the steels, i.e. the elastic modulus and Poisson's ratio, are the same and the conditions for linear elastic or small scale yielding behavior are fulfilled.

## DETERMINATION OF THE DYNAMIC FRACTURE TOUGHNESS BY IMPACT RESPONSE CURVES

With the impact response curve established, the dynamic fracture toughness of a given steel is determined by measuring the time to fracture in an impact experiment.

### Technique for Time to Fracture Measurements

The time to fracture of the specimen is obtained from signals of two uncalibrated strain gages, one of which is located on the tup of the hammer and the other on the specimen to the side of the crack tip. The leading edge of the signal from the hammer strain gage marks the beginning of the impact event. The onset of crack propagation, on the other hand, is indicated by the rapid drop in load registered by the crack tip strain gage. The records are electronically differentiated to give clear signals. The time to fracture $t_f$ is the interval between the two signals. A typical oscillogram for one experiment is shown in Fig. 5.

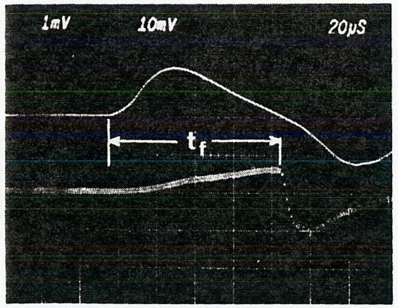

Fig. 5. Determination of the time to fracture $t_f$ from load signals registered at the hammer (upper trace) and the crack tip (lower trace)

### Experimental Procedure

Time to fracture measurements in impact tests with steel specimens were performed to check the applicability of the concept of impact response curves for determining the dynamic fracture toughness $K_{Id}$. Specimens from two different structural steels, 30 CrNiMo 8[2] and 15 MnNi 63[3], were used for these investigations. Specimen dimensions, crack lengths, and impact conditions were identical to those used to obtain the impact response curve. However, sharp crack tips produced by fatigue loading according to ASTM E 399 were utilized in these fracture toughness tests. Each specimen was instrumented by a strain gage at a distance of 6 mm to the side of the crack tip. The time between this signal and the hammer signal, i.e. the time to fracture, was automatically recorded during the test by an electronic counter. The specimens were tested at different temperatures.

### Experimental Results

Time to fracture data from 4 experiments with 30 CrNiMo 8 specimens tested at temperatures of -80°C and -60°C, and from 5 experiments with 15 MnNi 63 specimens tested at -110°C and -80°C are given in Table 1. The corresponding dynamic fracture toughness values $K_{Id}$ determined from the measured time to fracture values according to the previously established impact response curve are given in the last column of Table 1. All experiments were performed in the brittle fracture range. The time to fracture $t_f$ is less than the period $\tau$ of the specimen oscillation (calculated from eq. (2) to be 187 μs); thus condition (1) is not fulfilled and conventional measuring procedures would have failed. The crack tip loading rate $\dot{K}$ is of the order of $10^6 \mathrm{MN \cdot m^{-3/2} \cdot s^{-1}}$. Tests at higher temperatures were not performed with these specimens because of minimum size requirements.

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[2] Nominal composition: 2.1% Cr, 1.9% Ni, 0.3% Mo and 0.27% C, water quenched and tempered. Yield strength $\sigma_y$ = 995 MN/m$^2$, NDT-Temperature = (+25°C)

[3] Nominal composition: 1.6% Mn, 0.7% Ni and 0.17% C, heat treatment 530°C - 580°C for about 1 h in air. Yield strength $\sigma_y$ = 360 MN/m$^2$, NDT-Temperature < -28°C (-55°C)

TABLE 1 Experimental Data

| Steel | Test Temperature T, °C | Time to Fracture $t_f$, µs | Dynamic Fracture Toughness $K_{Id}$, $MNm^{-3/2}$ |
|---|---|---|---|
| 30 CrNiMo 8 | -82 | 73.5 | 57 |
| | -80 | 80.5 | 68 |
| | -80 | 74 | 58 |
| | -60 | 83.5 | 72 |
| 15 MnNi 63 | -109 | 88 | (79) |
| | -109 | 81 | 69 |
| | -109 | 76 | 61 |
| | -79 | 93.5 | 87 |
| | -79 | 87 | 78 |

Figures 6 and 7 show the obtained fracture toughness values $K_{Id}$ as a function of temperature and compare these data with available data (Verein Deutscher Eisenhüttenleute, 1975, 1979) for the static fracture toughness $K_{Ic}$ and the crack arrest toughnesses $K_{Ia}$ and $K_{Im}$. The relationship between the dynamic and the static fracture toughness values is plausible: The $K_{Id}$-values are lower than $K_{Ic}$, as is expected with these steels. The difference between the $K_{Ic}$- and $K_{Id}$-values is larger for the steel 15 MnNi 63 than for the higher strength steel 30 CrNiMo 8. An overestimation of the dynamic fracture toughness $K_{Id}$ in this brittle fracture range is not indicated. Furthermore, the dynamically determined crack arrest toughness value $K_{Im}$ measured at -110°C for the steel 15 MnNi 63 (Fig. 7) is about the same as the corresponding impact fracture toughness value $K_{Id}$. The statically determined crack arrest toughness $K_{Ia}$ due to neglected effects of recovered energy represents a lower bound approximation of the true crack arrest toughness.

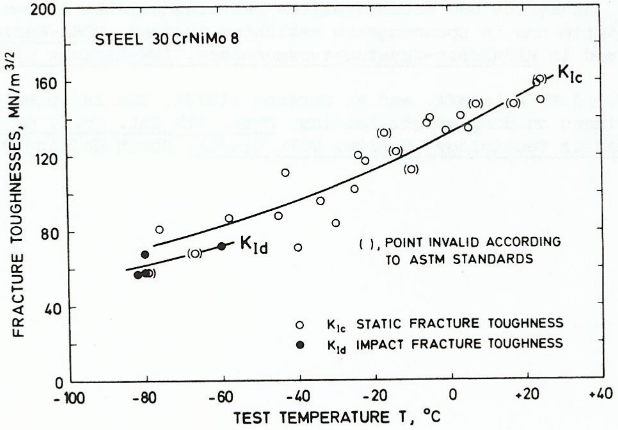

Fig. 6. Measured impact fracture toughness values $K_{Id}$ in comparison to other data for the steel 30 CrNiMo 8

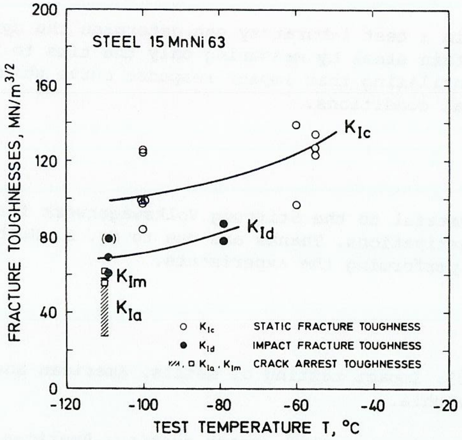

Fig. 7. Measured impact fracture toughness values $K_{Id}$ in comparison to other data for the steel 15 MnNi 63

## SUMMARY AND DISCUSSION

A measuring technique is described for determining the dynamic fracture toughness $K_{Id}$ in impact tests. The technique is based on

- impact response curves, $K_I^{dyn}(t)$, which are established by the shadow optical method of caustics in pre-experiments, and
- time to fracture measurements, which are performed in impact experiments with the structural steel to be investigated. There are several advantages of this measuring procedure with respect to the conventional technique for $K_{Id}$-determination.

The impact response curves represent a fully dynamic evaluation formalism. Kinetic effects are correctly taken into account for all times of the impact event. The method, therefore, can be applied for all experimental test conditions, in particular also in the small time to fracture range ($t_f < 3\tau$), i.e. when large specimens, high impact velocities, or brittle materials must be utilized. Even impact experiments at very high velocities, which exceed the usual 5 m/s obtained by a pendulum or a drop weight, can be evaluated. Such high loading rates are of importance for the determination of real lower bound fracture toughness data, $K_{IR}(T)$ needed for a conservative design of structures and components with stringent safety requirements.

The method does not require a calibrated instrumentation of the hammer which is usually needed in every impact experiment for determining the load at crack initiation. The present technique splits the measuring problem into two separate tasks: The determination of the impact response curve and the measurement of the time to fracture. The complicated determination of the impact response curve has to be carried out only once for a fixed experimental arrangement. A set of impact response curves for different experimental arrangements utilized in practice can be established. The actual $K_{Id}$-determination then requires only a relatively simple and inexpensive measurement of the time to fracture via uncalibrated instrumentations of the hammer and of the specimen. Investigations are currently performed to further simplify the procedure for the time to fracture measurement by avoiding instrumentation of the specimen itself.

Thus, an engineer in a test laboratory can determine the dynamic fracture toughness $K_{Id}$ for a certain steel by measuring only the time to fracture in an impact experiment and by utilizing that impact response curve which applies to the prevailing experimental conditions.

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