DETERMINATION OF THE DYNAMIC FRACTURE TOUGHNESS USING SUBSIZED SPECIMENS

H. Stroppe[+], R. Clos[+], U. Schreppel[+]

A new method for the determination of the dynamic initiation fracture toughness K_{Id} using subsized specimens is described. It may be used if only small specimens are available or safety regulations require such specimens, e.g. for neutron irradiated material. Results are given for a special steel and compared with K_{Id} values determined with other dynamic testing methods.

INTRODUCTION

The knowledge of the fracture toughness of steels at very high loading rates is important from the point of view of fundamental research as well as for a safety analysis. Some aspects, which are of practical relevance also, are:

- The dynamic initiation fracture toughness K_{Id} ($\dot{K}$, T) usually is the smaller the higher the loading rate parameter $\dot{K}$, T - Temperature. So one gets conservative fracture data.
- For the determination of valid fracture toughness values it is necessary to use specimens, which fulfill a condition of the kind

$$\text{all length} \gtrsim 2.5\,(K_{Id}/\sigma_d)^2 \quad \ldots\ldots\ldots\ldots\ldots (1)$$

[+] Technische Universität "Otto von Guericke" Magdeburg, Sektion Physik, Magdeburg, DDR

Because K_{Id} decreases with increasing loading rate while the dynamic yield strength σ_d increases high loading rate experiments require the smallest possible specimen size in principle.

At present there are at least three experimental setups e.g. by Costin et al (1), Stroppe et al (2) and Shockey et al (3), with which it is possible to determine K_{Id} for steels at $\dot{K}$-values between 10^6... 10^7 MPa $m^{1/2}$/s. In these setups the precracked specimen acts simultaneously as an elastic wave guide. The crack plane lies perpendicular to the specimen axis and a nearly plane tension wave, which propagates in the direction of the axis, interacts with the crack. The experiments differ mainly in the generation of the tension pulse and the specimen size.

As an example the setup used in (2) is shown in Fig. 2. The principle is the following. By the impact of the projectile a pressure pulse is generated in the bar. This pulse propagates through the bar and the acoustically coupled precracked specimen and is converted into a tension pulse by reflection at the free end B of the specimen. Experimentally the critical amplitude of the pulse is determined, which is necessary to cause crack growth. From this amplitude and a numerical elastodynamic analysis of the interaction pulse-crack the fracture toughness K_{Id} can be calculated. A similar practice is used in (1) and (3).

Unfortunately with such stress wave loading methods it is not possible to make the specimen length smaller than about the pulse length $L = c_0\ t_0$ (c_0 - bar velocity, t_0 - pulse duration, c_0 for steels about 5 mm/μs, smallest used t_0 about 20 μs) and this length is always much greater than the values given by eq. (1), while the dimensions of the cross section may be reduced to about 10 x 10 mm^2. Such cross section is used e.g. in the instrumented precracked Charpy test. This means, that a remarkable reduction of the specimen length requires a new loading arrangement.

The main advantage of the method proposed in the following is, that due to the small specimen size neutron irradiated material may be investigated more easy and e.g. the broken halfs of Charpy-V specimens can be used further to determine of the fracture toughness.

EXPERIMENTAL METHOD

The experimental setup is given in Fig. 1. A small three-point-bending specimen is situated between splitted Hopkinson pressure bars. In the input bar 1 a projectile generates a pressure pulse σ_I (t) (t - time). A so called bridge is coupled acoustically with the input bar and the fatigue precracked specimen. The other specimen surface by a small half cylinder is in acoustic contact with the transmitter bar 2. The incident stress pulse produces a loading situation of the specimen, which is similar to the so called "inverted instrumented Charpy-test", Rintamaa et al (4). Contrary to the latter there is a smooth rise of the loading force (bridge-specimen) and no impact loading of the specimen itself. At a sufficiently high amplitude of σ_I (t) crack propagation occurs.

The diameter of the bars is 20 mm. The bridge dimensions are 25 x 12.6 x 14 mm^3 and where choosen in such a way, that within a onedimensional wave analysis there is no reflection of σ_I at the boundary input bar-bridge. The specimen has a length l = 25 mm, width W = 10 mm, thickness B = 10 mm and the length a of the fatigue crack usually is 4...5 mm. The specimen is something smaller then one half of a Charpy-V-specimen. By means of the capacitive gauges the incident pulse σ_I , the reflected pulse σ_R (both in bar 1; a reflected pulse results from the free bridge surface and the interaction bridge-specimen) and the transmitted pulse σ_T (in bar 2) are measured. They are recorded with a digital oscilloscope (time resolution 0.2 μs). There is no instrumentation of the specimen itself.

The main part of σ_I is nearly squaresinus shaped. The trailing part contains oscillations with small amplitudes. The duration of the main part of σ_I is about 28 μs. Depending upon its amplitude one finds: no crack growth, crack growth with a finite change of the crack length or complete fracture of the specimen respectively. So by loading of several specimens with nearly identical initial crack length by pulses of different amplitude one finds experimentally a highest amplitude σ_1 , for which there is no crack growth (subcritical loading), and a smallest one σ_2 , for which crack growth occurs (supercritical loading). This is denoted as multi-specimen method. The investigations can be carried out at different temperatures.

Using these two stresses as well as the results of a numerical analysis one can calculate K_{Id} or more precise upper and lower bounds for K_{Id} at the given test temperature.

Some ideas of the analysis will be explained shortly, details will be published later.

Within the linear-elastic fracture mechanics the dynamic fracture toughness is defined as

$$K_{Id} = K_I(t = t_f) \quad \text{......................} (2)$$

where $K_I(t)$ is the time dependent stress intensity factor of the crack and t_f is the crack start time. Alternatively if the K_I-time-curve has a peak (and this is the case in pulse loading experiments), than crack growth occurs if Max $K_I(t)$ is greater than K_{Id} (supercritical loading). Contrary if Max K_I is lesser, than there is no crack growth (subcritical loading). Furthermore within linear elasticity the stress intensity factor (and its maximum also) must be proportional to the amplitude σ of the incident pulse. That means, there is a relation

$$\text{Max } K_I(t) = \sigma\, g(a,\ t_o,\ \ldots) \quad \text{..................} (3)$$

where g depends on the crack length a, the pulse duration t_0, the pulse shape (the experiments show, that $\sigma_I(t)/\sigma$ is practically a pure time function) and all other geometrical parameters. From this it follows

$$\sigma_1 g(a_1,\ t_o,\ldots) < K_{Id} < \sigma_2 g(a_2,\ t_o,\ldots) \quad \text{.......} (4)$$

where σ_1 and σ_2 are the experimentally determined stress amplitudes for subcritical and supercritical loading respectively. a_1 and a_2 are the corresponding crack length, which are nearly equal in the experiments.

In order to determine the function g a first numerical elastodynamic analysis of the system bar 1-bridge-specimen-bar 2 has been carried out by means of a finite difference method. A two-dimensional model of the real system was used. $K_I(t)$ has been calculated for different crack length and from this the function g. The results of the two-dimensional calculation has been corrected in an approximative way in order to take into account differences between the 2 D model and the real system, which is a three-dimensional one.

It is necessary to remark, that the shape and the duration of the transmitted pulse depends very sensitive upon the fact, if there is crack growth or not. So it seems possible, that one can determine K_{Id} using one specimen only in future.

RESULTS

A microalloyed steel H52-3Nb was investigated with the described method in a temperature range between 77 K and 243 K. The steel had a ferritic-pearlitic structure. At each test temperature the upper and lower bounds for K_{Id} has been calculated using eq. (4). The same steel but a different charge was investigated with the stress wave loading method after (2) also. The results are shown in Fig. 3. For comparison a few K_{Id} from the instrumented Charpy test (same charge) are given additionally.

It can be seen, that the new method and the method (2) give nearly the same K_{Id}-values at low temperatures. At higher temperatures there are some differences, which can have two reasons. First the two investigated charges can differ in the fracture toughness slightly. Second the cross section of the specimens used in method (2) is 17.7 x 17.7 mm^2, that means greater than in the new method (10 x 10 mm^2). So it is possible, that at higher temperatures the K_{Id} - values of the new method do no more fullfill the plane strain condition eq. (1), this would result in apparently higher K_{Id}. The differences to the instrumented Charpy data can be explained by the much smaller loading rate of this test in comparison to the new method and the stress wave loading method.

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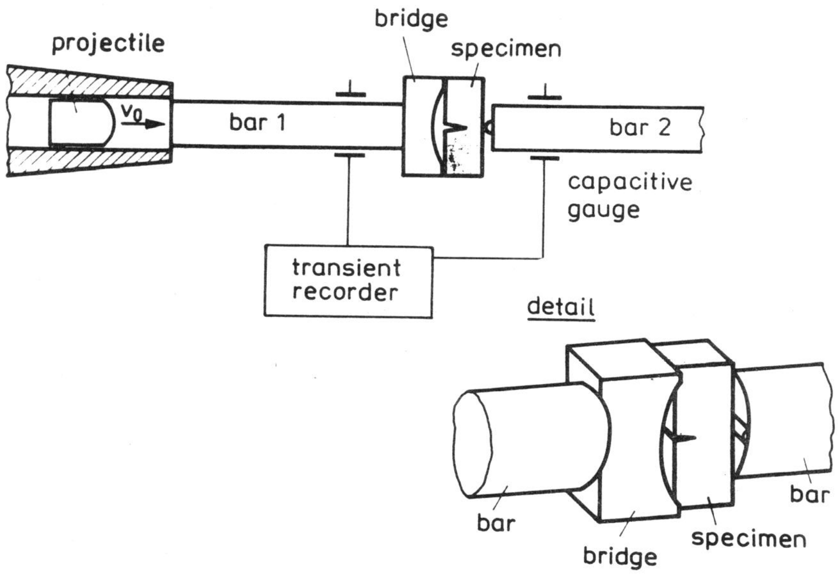

Figure 1 Experimental setup

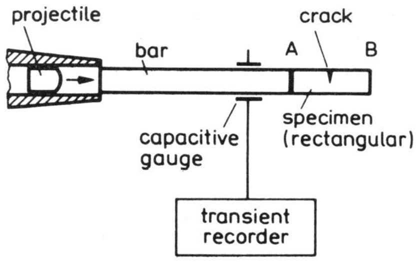

Figure 2 Stress wave loading method after (2)

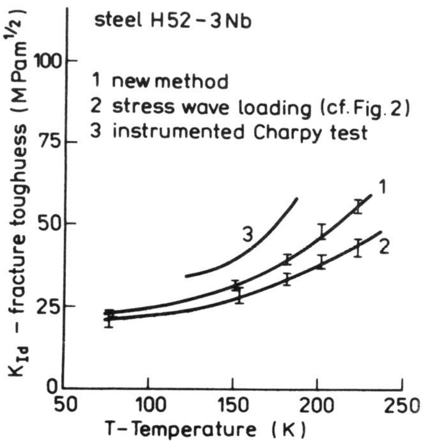

Figure 3 Fracture toughness versus temperature