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Dynamic crack initiation measurements in a four-point split Hopkinson bending device

Sebastian Henschel *, Lutz Krüger

Institute of Materials Engineering, TU Bergakademie Freiberg, Gustav-Zeuner-Str. 5, 09599 Freiberg, Germany

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ABSTRACT

A method is proposed for determining the resistance against dynamic crack initiation during elastic–plastic fracture. To this end, the split Hopkinson pressure bar principle was applied. Dynamic loading rates of $\dot{K} \approx 10^6\ \mathrm{MPa}\sqrt{\mathrm{m}}/\mathrm{s}$ were achieved. A small cross-sectional area of incident and transmission bar resulted in a highly sensitive force measurement. From the wave analyses, it was concluded that the dynamic force equilibrium was achieved before dynamic crack initiation took place. The resistance against dynamic crack initiation was described by the J integral. The dynamic crack growth could not be characterised due to a non-equilibrium state.

1. Introduction

There are several research groups that use the Hopkinson pressure bar principle to determine dynamic fracture toughness, e.g. [1–13]. Some of these investigations are based on force measurements on only one bar, where the specimen is placed in fixed supports [1,4–9]. Hence, analysis of the force equilibrium is, at best, difficult. Therefore, the split-bar or two-bar setup is applied to analyse the load history on both the loading and the support faces of the sample. The three-bar setup, with two bars acting as transmission bars, is another possibility for analysing the force equilibrium [14].

Weerasooriya et al. [10] present a split Hopkinson pressure bar, which applies four-point bending. Jiang and Vecchio [15] propose a similar setup, where the support pins are placed in grooves in the faces of the bars. The bars in this investigation were made of high-strength aluminium and had a diameter of 38 mm. Due to the bars limited diameter, the samples had a thickness of $B = 4$ mm, a length of $L = 40$ mm, and a width of W of 6.5 or 10 mm. The specimens were made of a high-strength Fe–10Cr steel, and were tempered at a range of temperatures to obtain different strength and toughness behaviours. However, no characteristic value (K_{Id} or J_{id}) describing the materials dynamic crack resistance is given. Another possibility for four-point bending in a split Hopkinson pressure bar setup is demonstrated by Foster et al. [2]. Here, the loading of bigger specimens ($B = 7.5$ mm, $L = 63.5$ mm, $W = 15$ mm) is achieved by impact and support tups, which are mounted at the faces of the bars. The high-strength 4340 steel (45 HRC) investigated in that study exhibits brittle fracture. Tanaka and Kagatsume demonstrate in [16] the applicability of a tube as a transmission bar. It is therefore possible to use a specimen shape similar to the Charpy geometry with a notch radius of 1 mm. In that study, the loading pin and the specimen's supports were separate parts which were screwed into each bar. Due to its relatively low hardness, the C45 steel investigated showed elastic–plastic behaviour even at low temperatures. However, only information about the absorbed energy was

* Corresponding author. Tel.: +49 3731 393452; fax: +49 3731 393703.
E-mail address: sebastian.henschel@iwt.tu-freiberg.de (S. Henschel).

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Nomenclature

a_0	initial crack length
$B; B_N$	specimen's thickness; specimens's thickness (side-grooved)
$c_0; c_l; c_s$	sound velocity: bar (1-dimensional propagation); longitudinal wave; shear wave
C	compliance
d	diameter
E	modulus of elasticity
f	midspan deflection of the sample
F	force
J	J integral
$K; \dot{K}$	stress intensity factor (SIF); rate of the SIF
L	specimen's length
$R_{p0.2}(\dot{\varepsilon})$	0.2% offset yield strength at strain rate
S	support span
t, t'	time
U_p	plastic work
v_B	velocity of the bar
W	specimen's width
z	displacement of the bar

Greek symbols

δ	relative displacement
Δ	distance between crack and strain gauge
$\varepsilon; \dot{\varepsilon}$	strain; strain rate
ν	Poisson's ratio
ϱ	density
σ	stress

Subscripts

1; 2	Interface 1 (end of incident bar); Interface 2 (beginning of transmission bar)
I; R; T	incident; reflected; transmitted
IB; TB; SG	incident bar; transmission bar; strain gauge
S; B	specimen; bar

obtained. Moreover, no fracture-mechanical analysis was possible due to the absence of a precrack. Based on the setup in [16], Kulin et al. [11] modified the four-point bending setup in [15] by applying a tube as the transmission bar. Hence, the sensitivity of the transmission bar increased by its adjusted cross section.

Force equilibrium in the sample is a crucial point during determination of the specimens loading and of its response. According to Owen et al. [17], a quasi-static solution for the stress intensity factor can then be used to calculate the specimens loading. The force equilibrium is determined by analysing the force in both the incident bar and the transmission bar. If these two forces are equal or have only minor differences (e.g. small symmetrical oscillations), force equilibrium is achieved [18]. Therefore, inertial effects disappear if the difference of the forces in the incident bar and transmission bar is zero [12]. The calculation of the specimen loading by the deflection of the specimen as shown in [1] is, however, possible if the displacement of the loading and the support is known. Otherwise, a force equilibrium has to be assumed, which is not the case in [1].

In order to achieve force equilibrium, the specimen loading must be in-phase with the force applied by the bars. According to Weerasooriya et al. [10], this requirement is achieved by a limited frequency spectrum of the incident pulse. The upper limit is given by the first resonant frequency of the specimen with its boundary conditions given by the loading and support pins [10]. Hence, there is an upper limit for the slope of the incident pulse. Frequency components of the incident pulse higher than the first resonant frequency result in a phase offset (180°) of these components of the transmitted pulse [10,19]. Consequently, the loss-of-contact phenomenon can occur [20].

Dynamic effects attenuate with time. A transition time after that a dynamic calculation leads to the same results as the quasi-static assumption was studied in [21–24]. The transition time can be determined experimentally [23] or numerically [21,22,24]. In Böhme [23], the transition time was determined to be $t_T = 12.3W/c_{l,S}$ ($L/W = 5.5, a/W = 0.5$). According to Koppenhoefer [21], the transition time is impact velocity dependent and can be estimated by $t_T = 13W/c_{l,S}$ for high impact velocities of 3–6 m/s. Dutton and Mines [22] model the Hopkinson pressure bar setup with an inertia model and calculate a transition time of $t_T = 1.1\tau$. The apparent time of specimen oscillation τ is estimated by Ireland [25]: