A NOVEL PROCEDURE FOR MEASURING THE IMPACT FRACTURE TOUGHNESS KId WITH PRECRACKED CHARPY SPECIMENS

J. Kalthoff, S. Winkler, W. Böhme

To cite this version:

J. Kalthoff, S. Winkler, W. Böhme. A NOVEL PROCEDURE FOR MEASURING THE IMPACT FRACTURE TOUGHNESS KId WITH PRECRACKED CHARPY SPECIMENS. Journal de Physique Colloques, 1985, 46 (C5), pp.C5-179-C5-186. <10.1051/jphyscol:1985523>. <jpa-00224753>

HAL Id: jpa-00224753
https://hal.archives-ouvertes.fr/jpa-00224753
Submitted on 1 Jan 1985

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
A NOVEL PROCEDURE FOR MEASURING THE IMPACT FRACTURE TOUGHNESS $K_{Id}$ WITH PRECRACKED CHARPY SPECIMENS

J.F. Kalthoff, S. Winkler and W. Böhme

Fraunhofer-Institut für Werkstoffmechanik, Wöhlerstrasse 11, D-7800 Freiburg, F.R.G.

Abstract - A procedure is presented for determining the impact fracture toughness $K_{Id}$ with precracked Charpy specimens without performing any load measurements. The $K_{Id}$-value is obtained from preestablished impact response curves and a measurement of the time-to-fracture. The measuring technique is fully dynamic and does not impose any restrictions on the test conditions. The applicability of the measuring procedure is demonstrated by determining the impact fracture toughness of two different steels at different test temperatures.

I - INTRODUCTION

Instrumented impact tests with precracked Charpy specimens are often used to measure the impact 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. A standard method of test proposed to ASTM [1] is based on this measuring principle.

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, particularly when the early time range is considered, and secondly, because a dynamic material strength value is inferred from a static evaluation analysis.

This conventional measuring technique, therefore, can only yield meaningful data if fracture occurs after times sufficiently large that a quasistatic loading condition has been reached in the specimen. The ASTM-method assumes that this condition is fulfilled when the time-to-fracture, $t_f$, of the specimen is larger than three times the period $\tau$ of the oscillation of the impacted specimen:

$$t_f > 3\tau$$

(1)

with $\tau = 45$ to 60 $\mu$s, depending on the length of the starter crack. The condition (1) restricts the range of applicability of the test: Sufficiently large times-to-fracture are only achieved if the ductility of the material under study and the test temperature are sufficiently high and/or if the impact velocity is sufficiently low.
The maximum allowable impact velocity depends on the toughness of the material to be measured. Thus, tests cannot be performed over a large range of temperatures at the same impact velocity. These difficulties and restrictions are overcome by applying the concept of impact response curves for measuring the impact fracture toughness $K_{1d}$. This concept has originally been developed by the authors for large bend specimens tested in drop weight towers [2-5]. This paper and a corresponding article in the Metals Handbook [6] describe an extension of this measuring methodology for precracked Charpy specimens with special emphasis to routine applications in laboratory tests.

II - BASIC PRINCIPLE OF THE MEASURING PROCEDURE

For fixed test conditions, such as specimen geometry (in particular crack length) and impact velocity, the history of dynamic crack tip stress intensity factor, $K_{I}^{dyn}(t)$, is established for the specific impact process considered. This $K_{I}^{dyn}(t)$-curve quantitatively relates the response of the specimen to the impact event and therefore is called the "impact response curve". This curve depends only on the elastic reaction of the specimen-striker system and therefore is unique for the system considered and applies to all steel specimens tested under the same impact conditions. Consequently, this one relationship applies to 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 fracture mechanics or small-scale yielding behavior are fulfilled.

![Diagram showing determination of dynamic fracture toughness $K_{1d}$](image)

Fig. 1 - Determination of the dynamic fracture toughness $K_{1d}$ by impact response curves

The dynamic fracture toughness for a given structural steel is then determined by performing an impact experiment with a specimen made from the steel under study and measuring the resulting time-to-fracture. The dynamic fracture toughness value $K_{1d}$ is obtained from the preestablished impact response curve and the measured time-to-fracture $t_f$ (see Fig. 1) by using the relation:

$$K_{1d} = K_{I}^{dyn}(t = t_f) \tag{2}$$

This fully dynamic procedure for measuring the impact fracture toughness does not have the previously discussed restriction that the time-to-fracture must be larger than a certain minimum value (see Eq. (1)). Therefore, the procedure can be applied for all experimental test conditions, particularly also in the brittle fracture and high-velocity impact range, as long as the usual conditions for small-scale yielding are fulfilled.
III - IMPACT RESPONSE CURVES

The impact response curves can be measured or calculated. Pure numerical calculations generally would require the consideration of both the specimen and the striking hammer. Numerical efforts are reduced considerably if experimental data, such as the load or displacement history measured at the tup of the striking hammer, are used as input data for the numerical calculation. Efforts to establish numerical relationships quantifying the specimen response during the impact process have been undertaken by various investigators [7-14]. Systematic studies on the basis of semi-analytical considerations discuss the specific influence of individual test parameters [15,16]. Experimental techniques based on optical methods, e.g. the photoelastic technique of isochromatic fringes and the shadow optical method of caustics [17,18], are applicable but preferably are to be used with specimens that are larger than Charpy specimens, such as specimens used in drop weight arrangements [2-4, 9-11, 17,18].

Strain gage instrumentation of the specimen near the crack tip provides the simplest way to establish impact response curves with precracked Charpy specimens (see e.g. [19]). In a static preexperiment, the signal obtained from a strain gage at a specific location near the crack tip is calibrated in terms of the stress intensity factor. Because the strain gage is located near the crack tip, the strain gage signal obtained in an impact event can be assumed to represent a good measurement of the dynamic crack tip stress intensity factor as well.

Figure 2 illustrates impact response curves for steel Charpy specimens with an initial crack length of \( a = 5 \) mm tested at different impact velocities of \( v_0 = 2, 3.8, \) and \( 5 \) m/s. The data were obtained with a 300 J pendulum test device (tup radius 2 mm, machine compliance \( C_M = 8.1 \times 10^{-9} \) m/N). The strain gages were positioned about 2 mm to the side of the crack tip. To increase the load-carrying capacity of the specimen, blunted notches instead of fatigue-sharpened initial cracks were utilized in the experiments.

The impact response curves for different impact velocities are similar. The stress-intensity factors \( K_{IY} \) depend linearly on the impact velocity \( v_0 \). Furthermore, the data are independent of the hammer mass \( m_h \), provided the energy used for breaking the specimen is small compared to the total impact energy [16]. This condition is usually fulfilled with conventional pendulum impact test devices, if the specimen breaks in the early time range. The impact response curves for arbitrary impact
velocities can therefore be represented by a single relationship. It can be seen from Figure 2 that this relationship can be mathematically described by a linear dependence of $K$ on time with superimposed dynamic corrections. This relationship differs with crack length, but for the small variations in crack length used in bend specimens ($0.45 < a/W < 0.55$ as recommended in ASTM E 399), the resulting differences are only modest and can be compensated for in an approximate manner.

For practical applications, it is convenient to use the expression:

$$K_{\text{dyn}} = R \cdot v_0 \cdot t''$$  \hspace{1cm} (3)

where $t'' = f(t')$ given by Table 1

$$t' = g(t) = t \left[ 1 - 0.62(a/W - 0.5) + 4.8(a/W - 0.5)^2 \right]$$

with $R = 301 \text{ GN/m}^5/2$ (1). $v_0$ is the impact velocity, $a$ is the crack length, $W$ is the specimen width, $t''$ and $t'$ are modified times, and $t$ is the measured physical time. The functions $f$ and $g$ account for the dynamic corrections and variations of crack length, respectively.

<table>
<thead>
<tr>
<th>$t'$</th>
<th>$t''$</th>
<th>$f(t')$</th>
<th>$t'$</th>
<th>$t''$</th>
<th>$f(t')$</th>
<th>$t'$</th>
<th>$t''$</th>
<th>$f(t')$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
<td>18</td>
<td>194</td>
<td>200</td>
<td>18</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>102</td>
<td>20</td>
<td>204</td>
<td>202</td>
<td>20</td>
<td>204</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>104</td>
<td>22</td>
<td>204</td>
<td>204</td>
<td>22</td>
<td>204</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>106</td>
<td>24</td>
<td>206</td>
<td>206</td>
<td>24</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>108</td>
<td>26</td>
<td>208</td>
<td>208</td>
<td>26</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>110</td>
<td>28</td>
<td>210</td>
<td>210</td>
<td>28</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>112</td>
<td>30</td>
<td>212</td>
<td>212</td>
<td>30</td>
<td>212</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>14</td>
<td>114</td>
<td>32</td>
<td>214</td>
<td>214</td>
<td>32</td>
<td>214</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>116</td>
<td>34</td>
<td>216</td>
<td>216</td>
<td>34</td>
<td>216</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>18</td>
<td>118</td>
<td>36</td>
<td>218</td>
<td>218</td>
<td>36</td>
<td>218</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>120</td>
<td>38</td>
<td>220</td>
<td>220</td>
<td>38</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>22</td>
<td>122</td>
<td>40</td>
<td>222</td>
<td>222</td>
<td>40</td>
<td>222</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>24</td>
<td>124</td>
<td>42</td>
<td>224</td>
<td>224</td>
<td>42</td>
<td>224</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>26</td>
<td>126</td>
<td>44</td>
<td>226</td>
<td>226</td>
<td>44</td>
<td>226</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>28</td>
<td>128</td>
<td>46</td>
<td>228</td>
<td>228</td>
<td>46</td>
<td>228</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>130</td>
<td>48</td>
<td>230</td>
<td>230</td>
<td>48</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>32</td>
<td>132</td>
<td>50</td>
<td>232</td>
<td>232</td>
<td>50</td>
<td>232</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>34</td>
<td>134</td>
<td>52</td>
<td>234</td>
<td>234</td>
<td>52</td>
<td>234</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>36</td>
<td>136</td>
<td>54</td>
<td>236</td>
<td>236</td>
<td>54</td>
<td>236</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>38</td>
<td>138</td>
<td>56</td>
<td>238</td>
<td>238</td>
<td>56</td>
<td>238</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>140</td>
<td>58</td>
<td>240</td>
<td>240</td>
<td>58</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>42</td>
<td>142</td>
<td>60</td>
<td>242</td>
<td>242</td>
<td>60</td>
<td>242</td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>44</td>
<td>144</td>
<td>62</td>
<td>244</td>
<td>244</td>
<td>62</td>
<td>244</td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>46</td>
<td>146</td>
<td>64</td>
<td>246</td>
<td>246</td>
<td>64</td>
<td>246</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>48</td>
<td>148</td>
<td>66</td>
<td>248</td>
<td>248</td>
<td>66</td>
<td>248</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 - Time function

(1) This value for $R$ applies for stiff test devices with a machine compliance $C_M = 8.1 \times 10^{-9} \text{ m/N}$. If the compliance of a test device should be different, the resulting influence can be taken into account by multiplying the given value of $R$ by the first-order correction factor $1.276/(1 + 0.276 C_M/8.1 \times 10^{-9} \text{ m/N})$. Procedures for determining the machine compliance of impact test devices are described in [20].
This approximate formula shows good agreement when compared with semianalytical results \cite{16}. Equation (3) describes the impact response curves for all practically relevant test conditions with an accuracy sufficient for engineering purposes.

IV - TIME-TO-FRACTURE MEASUREMENTS

The time-to-fracture of a precracked Charpy specimen subjected to impact loading can be obtained from signals of two uncalibrated strain gages, one of which is located on the tup of the striking 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 time-to-fracture, $t_f$, is the interval between the two signals. Typical oscillograms of time-to-fracture measurements are shown in Figure 3.

An indication of the time at which the crack becomes unstable can also be obtained by another procedure, which does not require specimen instrumentation. At the onset of rapid crack propagation, a magnetic signal is generated by the accelerating crack tip if the specimen has been slightly magnetized before testing, e.g. with a permanent magnet \cite{21}. This signal is picked up by a magnetic sensor (e.g. a coil) located at the crack tip near (but not in contact with) the specimen surface. Very good results have been obtained with commercially available magnetic pickups that are used in tape recorders.

The signal thus obtained has a short rise time and gives a clear indication of the time at the moment of fracture instability. Figure 3 shows a magnetic crack initiation signal compared to a crack tip strain gage signal. This magnetic measuring procedure is inexpensive and highly advantageous for routine testing, because it does not require extensive or costly specimen instrumentation.

Examples of impact fracture toughness data, $K_{ic}$, are shown in Figure 4 a and b. Specimens made of the steels 30 CrNiMo 8 and 2E6 460 (see inserts in Fig. 4 for nominal compositions) were tested at different temperatures at impact velocities of 5 or 2.5 m/s. Times-to-fracture in the range of 18 to 95 $\mu$s were measured. Despite the small times, $t_f < 3\tau$, the impact response curve technique yields reliable and mea-
ningful $K_{Id}$ data, as indicated by a comparison with equivalent static fracture toughness data, $K_{IC}$.

![Graph](image)

**STEEL 30CrNiMo8**

Nominal Composition:
1.52% Mn, 1.9% Ni, 0.18% V, 0.28% Si, 0.09% P, 0.09% S, 0.27% C

$G_y = 995 \text{ MN/m}^2$

**STEEL StE 460**

Nominal Composition:
1.52% Mn, 0.62% Ni, 0.16% V, 0.28% Si, 0.06% P, 0.09% S, 0.27% C

$G_y = 480 \text{ MN/m}^2$

The technique of measuring impact fracture toughness $K_{Id}$ with impact response curves and time-to-fracture measurements has several advantages over the conventional quasistatic ASTM-procedure [1]. The impact response curve technique represents a fully dynamic evaluation. Kinetic effects are correctly accounted for during the entire impact event. The method can thus be applied to all experimental test conditions, particularly also in the small time-to-fracture range ($t_f < 3 \tau$), i.e. when high impact velocities are used or brittle materials are tested.
This method does not require a calibrated instrumentation of the hammer, which is usually a prerequisite in impact experiments designed to determine the load at crack initiation. The data measuring procedure consists of two separate tasks: the determination of the impact response curve and the measurement of the time-to-fracture. The more complicated determination of the impact response curve needs only be carried out once. An approximate formula for impact response curves has been established that applies to different experimental conditions of practical concern. The actual \( K_d \) determination requires only a relatively simple and inexpensive measurement of the time-to-fracture. Time-to-fracture, in turn, can be determined from signals obtained by uncalibrated instrumentations of the hammer and the specimen. Specimen instrumentation can also be avoided by sensing the magnetic signal generated by the crack at the moment of fracture instability. Thus, the impact fracture toughness \( K_d \) of a given steel is determined by measuring only the time-to-fracture in an impact experiment and by utilizing the particular impact response curve that applies to the prevailing experimental conditions.

The concept of impact response curves extends the conventional quasistatic evaluation procedure into the lower time-to-fracture range. It is an appropriate measuring tool for testing specimens that fail at relatively short times after impact, i.e. the procedure is particularly suitable for testing at high impact velocities and for testing brittle materials. The applicability range of the procedure is limited by the usual small-scale yielding conditions, because the uniqueness of impact response curves is lost when large plastic deformations are present. Under the conditions of large plastic deformations, however, the resulting times-to-fracture generally are sufficiently long so that the quasistatic evaluation procedure can be applied successfully. Both procedures therefore have their specific ranges of applicability and complement each other.

REFERENCES


