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EVALUATION OF DYNAMIC FRACTURE TOUGHNESS J_{Id} USING INSTRUMENTED CHARPY IMPACT TEST

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This paper presents two methods of calculation of dynamic fracture toughness J_{Id} for 40 HMNA steel. In this study, it is attempted to detect the crack initiation moment by calculating the compliance changing rate from a load-deflection curve obtained in the instrumented Charpy impact test. Next, a J-Δa curve is estimated by using the stop block test which is a multiple specimen technique. The above results are compared to those obtained with the aid of technique based on the F_{max} concept.

1. Introduction

Determination of the fracture toughness in materials under dynamic loading is a subject of numerous theoretical and experimental papers (cf Hutchinson, 1968; Rice, 1968; Kobayashi, 1983; Kobayashi, Yamamoto and Ninomi, 1986; Kobayashi and Ninomi, 1989). Despite of some doubt an attempts are also undertaken to introduce standards in order to determine these parameters. One of the fracture toughness parameters, widely accepted, is a dynamic stress intensity factor K_{Id} which is applicable to brittle or semi-brittle materials. Although, from the physical point of view, the K_{Id} factor is well founded, the methods of its determination are often not acceptable. The standard method proposed by ASTM (1980) was convincingly questioned by Rokach (1993).

The problem is much more complex when applied to the ductile materials (where $r_p > 0.02a$, r_p is the length of a plastic zone and a is the length of a crack). For such materials the K_{Id} factor can not be used because of theoretical origins of this parameter. Therefore, the other parameter which is proposed to replace K_{Id} in plastic materials is J-integral. The J-integral is equivalent to the stress intensity factor (SIF), being an amplitude of the singular stress-strain field in front of the crack (HRR-field) (cf Hutchinson, 1968) in nonlinear materials. In plastic materials the path invariance of the J-integral can be proved for the deformation theory of plasticity and for static cases only. However, at the moment, fracture mechanics does not provide us with other parameters that can represent the fracture toughness in plastic materials under dynamic loading. For these reasons, the J-integral is usually computed according to the classical Rice's definition (cf Rice, 1968).

The critical value of J-integral, measured in dynamic tests is not a material parameter. Nevertheless, it provides more information about material than the classical Charpy test. It is the only reason for a great number of researchers trying to find the proper technique in order to measure the J-integral under dynamic loading. In fact, existing methods are not univocal and they arise many difficulties of technical and interpretative nature. These problems are the subject of presented paper.

Computation of the critical value of J-integral at the moment of crack initiation requires the measurement of the work U that is necessary to initiate the crack growth. It is not difficult to measure U or its rates but the problem arises when one wants to determine the moment of crack initiation and increments of the crack length Δa. The existing methods of experimental determination of Δa and the moment of crack initiation e.g. the potential drop method, are very difficult to be implemented into the case under dynamic loading. Similarly, acoustic emission, and crack mouth opening methods are not easy to be applied under these conditions. They need a deep research to gain experience in interpretation of results.

The experimental part of the presented research has been carried out in laboratories of EMPA, Dübendorf, Switzerland. Here, we report only this portion of the research program that allows one to determine the J_d value using the method of stop block (SB) and the method of compliance changing rate (CCR).

The instrumented Charpy pendulum with detectors of basic signals, a fast oscilloscope with memory and numeric registers were used. The computer program (EMPA_TUK) that allows for conversion and analysis of obtained signals has been created. In the literature (cf Kobayashi, Yamamoto and Ninomi, 1986) the above experimental setup to determine the dynamic toughness in materials is known as CAI (Computer Aided Instrumented Charpy impact Testing System). Utilizing $F = f(t)$ signal (where F is the Force recorded from the pendulum tup and t is time) the CCR method was used to detect the moment of crack initiation. According to the author's knowledge the experimental procedure, when only one recorded signal was used, had not been adopted earlier.

The results obtained were compared with those computed using the concept of F_{max} and the SB method.

2. Experiment

2.1. Material

The material used was 40HMNA steel (PN-72/H84030). It is chromium-nickel-molybdenum steel, used to produce highly strained machine elements, automobiles, engines and airplanes. This is high-strength steel revealing high resistance to the impact loading. 40HMNA steel is similar to the 4340 one (ASTM A322-64a, ASTM A505-64). They differ only in the Nickel content ($1.25 \div 1.65\%$ and $1.65 \div 2.0\%$). The chemical composition is given in Table 1. The specimens were oil hardened (1123 K) and tempered (893 K). The yield and ultimate strength were, respectively, $R_e = 995$ MPa, $R_m = 1090$ MPa.

Table 1. Chemical composition (% by weight)

Fe	C	Mn	Si	P	S	Cr	Ni	Cu	Mo
95.821	0.447	0.723	0.376	0.0155	0.0190	0.750	1.42	0.123	0.17

2.2. Geometry of the specimen

The typical Charpy $10 \times 10 \times 55$ mm specimen with machined notches were used. The specimens were precracked by the three-point bending fatigue.

2.3. Measurement of the dynamic fracture toughness J_d

2.3.1. Stop block technique

The method of R-curve obtained with the help of SB technique is a multi-specimen method. To obtain the $J - \Delta a$ curve specimens with various crack length increase values are utilized. The standard Charpy pendulum must be

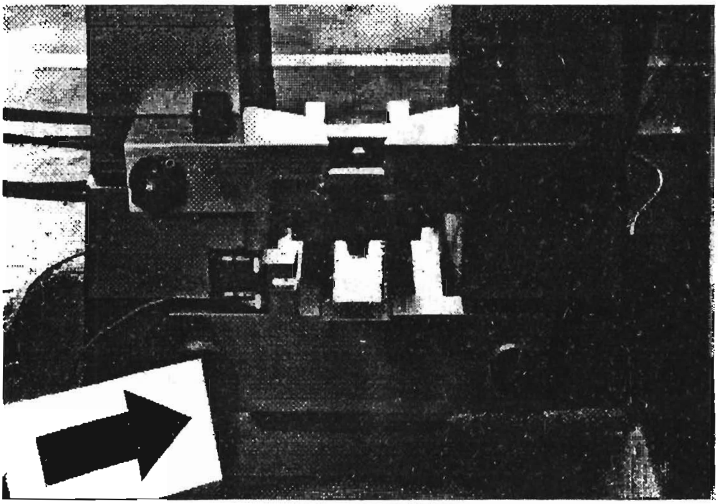

Fig. 1. Photograph of the stop block

equipped with a special device of much higher stiffness than pendulum. This device is called the stop block and it absorbs energy of a moving pendulum. In Fig.1 the stop block used in experiment is presented. The change in the crack length can be controlled by the change of the position of the crack front. The $J - \Delta a$ relation can be computed with the help of the following relation (cf Rice, 1968)

$$J = \frac{2}{(W - a_0)B} \int\limits_0^{\delta^*} F \, d\delta \tag{2.1}$$

where

W, B	–	height and thickness of the specimen
a_0	–	initial length of the crack
F	–	force recorded during the test
δ	–	deflection of the specimen
δ^*	–	deflection of the specimen corresponding to the actual position of the stop block.

After the stop block test the specimens were heated to the temperature 573 K (temperature of a blue color) and broken at the temperature of liquid nitrogen. In Fig.2 several specimens are shown with different final lengths of the crack.

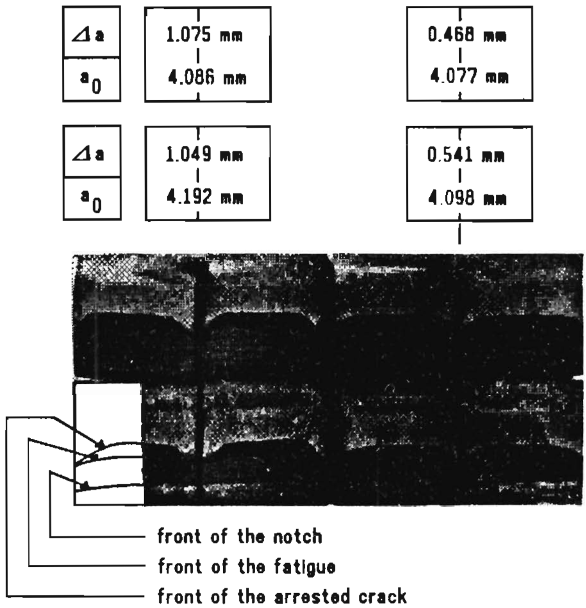

Fig. 2. Specimens with arrested cracks during SB test

2.3.2. Compliance changing rate method

The crucial problem in a dynamic fracture test is determination of the crack growth initiation moment and consequently the amount of energy corresponding to this moment. It has already been mentioned that the methods used in static tests are useless in dynamic tests.

An intensive research on finding the proper techniques have been observed over the last decade. An example of the successful attempt is a compliance changing rate method applied first by Tseng and Markus (1982) for aliminium alloys and by Kobayashi (cf Kobayashi, 1983; Kobayashi, Yamamoto and Ninomi, 1986; Kobayashi and Ninomi, 1989) for steels. The method requires a solution to the following relation with the help of properly arranged experiment

$$\Delta C C_{el}^{-1} = (C - C_{el}) C_{el}^{-1} \tag{2.2}$$

where

ΔCC_{el}^{-1}	–	compliance changing rate
C	–	compliance measured along the $F = f(s)$ curve
C_{el}	–	elastic compliance measured along the linear-elastic part of the $F = f(s)$ curve
F	–	external force
s	–	deflection of the specimen.

C_{el} can be determined as $C_{el} = F_Y/\Delta s_Y$, where F_Y is the yield point load and Δs_Y is the yield point deflection.

At a next step the curve $\Delta CC_{el}^{-1} = g(s)$ is ploted and the point of noticable change of its slope indicates the moment of the crack growth initiation. Using Eq (2.1) the critical value of J-integral (J_{dc}) can be computed.

Scheme of graphical determination of the crack initiation moment is shown in Fig.3.

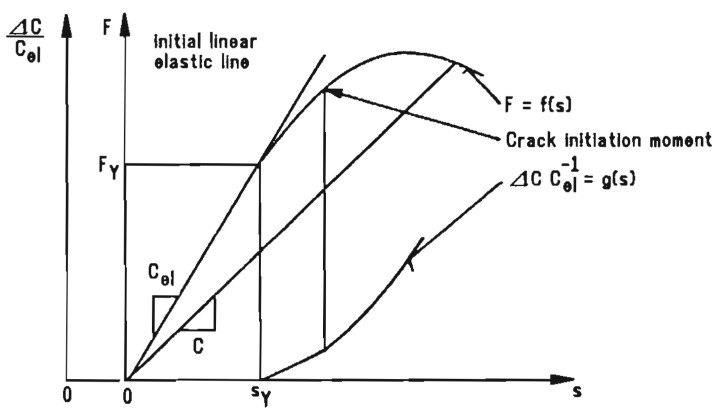

Fig. 3. Scheme of initiation moment determination with the help of CCR method

2.4. Determination of the force-deflection relation

In most of the dynamic tests done with the help of Charpy pendulum two signals are recorded simultaneously. They are: force (using strain gauge transducers) and specimen deflection (using other indirect methods e.g. optical methods).

However, adopting the energy and momentum equilibrium laws of the pendulum-specimen systems one can obtain the deflection-time relation

$$s(t) = \int_{t_0}^{t} \Big(v_0 - \frac{1}{m} \int_{t_0}^{t^{**}} F(t^*)\,dt^*\Big)\,dt^{**} \tag{2.3}$$

where

v_0 – initial impact velocity

m – mass of the pendulum

t_0, t – times of the beginning and end of the deformation process, respectively.

We have applied Eq (2.3) to calculate the results presented in this paper.

2.5. Experimental arrangement

All experimental results were obtained in Swiss Federal Laboratories for Materials Testing and Research in Dübendorf, Switzerland. The Charpy pendulum of maximum impact energy 300 J was produced by Wolpert Werkstoffprümmaschinen AG. The pendulum was equipped with the Nicolett oscilloscope with memory. As an additional equipment the analog transducer was used to determine impact velocity, displacement of the pendulum and its energy. The computer program was written to allow for a full analysis of a force-time signal. The pendulum was also equipped with magnetic and electron detectors. Analysis of these signals will be a subject of additional paper.

2.6. Experimental procedure

Specimens were pre-cracked before the test. The resonance electromagnetic generator of 200 Hz frequency was used in order to initiate fatigue crack. The length of the fatigue crack was automatically controlled by the change in specimen compliance. The specimens were exposed to 40 J energy (impact velocity $v_0 = 2.01$ m/sec) at various location of the stop block. After test the specimens were "coloured" at 473 K and fractured at the liquid nitrogen temperature.

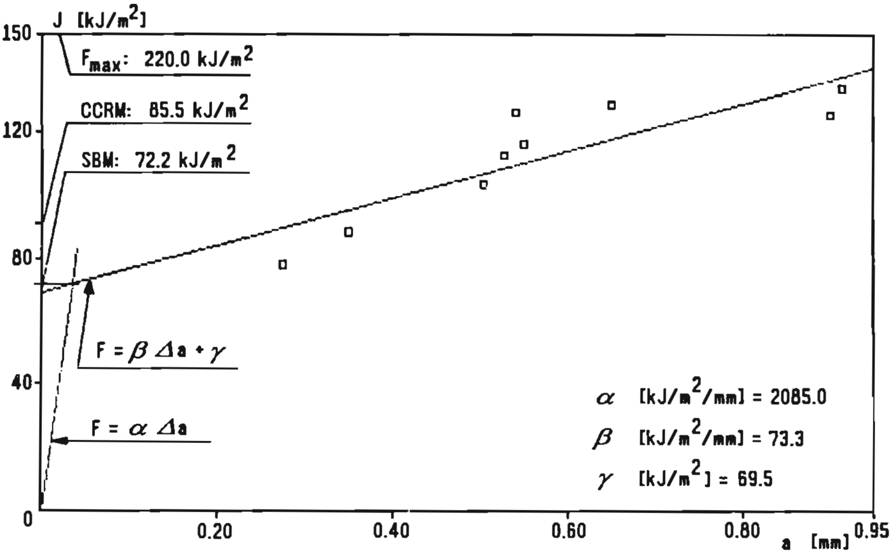

Fig. 4. Results of J evaluation with the SB method

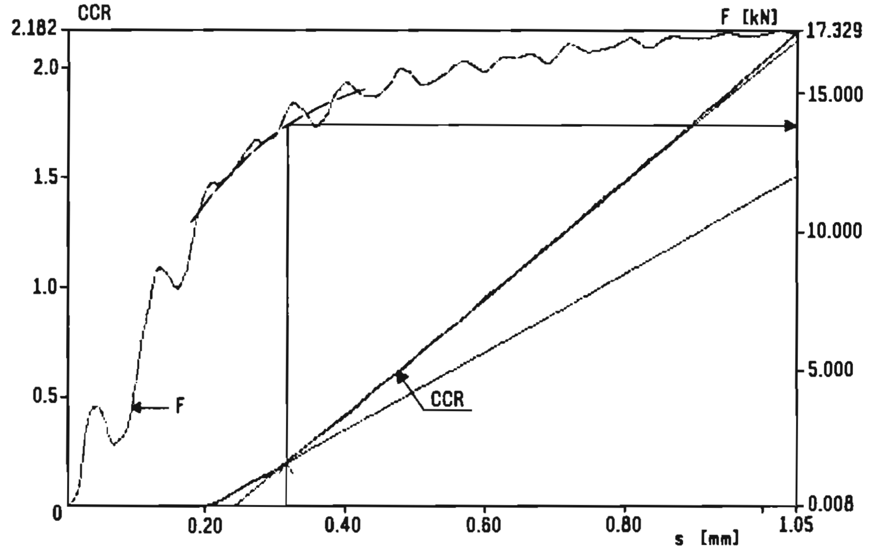

Fig. 5. Determination of the moment of crack growth initiation with the CCRM

3. Results and discussion

Results of the J-integral evaluation with the SB method are shown in Fig.4. In Fig.5 the results of CCR method are shown for one selected specimen. Results of presented research are given in Table 2.

Table 2. Results of tests

Method evaluation of J		
CCRM	SBM	$F_{\max}$
J_d [kJ/m^2]		
85.5	72.2	220.0

The results obtained by both SB and CCR methods show good agreement but they differ from that measured with the help of $F_{\max}$ criterion. The criterion $F_{\max}$ is certainly very easy to apply but has a peripheral practical meaning (cf Kobayashi, Yamamoto and Ninomi, 1986). The initiation of crack growth starts usually before the moment when external loading reaches the maximum value. Ambiquous is also the problem of determination of this maximum.

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Wyznaczenie dynamicznej odporności na pękanie metodą udarowego zginania

Streszczenie

W pracy wyznaczono miarę odporności stali 40HMNa na pękanie przy dynamicznym obciążeniu w postaci parametru J_d. Zastosowano metodę wielu próbek, która przy pomocy techniki "stop bloku" pozwoliła na wyznaczenie krzywej R. Krytyczną wartość J_{dc} porównano z wartością wyznaczoną metodą krzywej zmiany podatności oraz z wartością wyznaczoną w oparciu o punkt krzywej F, s odpowiadający F_{max}.

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