DETERMINATION OF DYNAMIC CRACK INITIATION TOUGHNESS BY THE INSTRUMENTED PRECRACKED CHARPY TEST

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The application of the precracked instrumented Charpy test for the determination of the dynamic R-curve and the fracture initiation toughness J_{di} in the upper shelf region of structural steels was studied. Different methods of the multiple specimen technique were compared with stretch zone measurements and a proposal was made to define dynamic fracture initiation toughness as a technical value $J_{d0.1}$.

INTRODUCTION

Fracture of ductile materials or during loading in the upper shelf region of ferritic steels is initiated by crack tip blunting with subsequent stable crack growth. In this case the application of the elastic-plastic R-curve methodology is required and the initiation toughness values J_i or δ_i are determined as characteristic fracture parameters. For static loading, these parameters can be found by

(a) plotting an R-curve (in terms of J or δ, respectively) by a multiple or single specimen method, and definition of the crack initiation toughness parameter close to the physical crack initiation

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point.

(b) direct monitoring of crack initiation during loading by a highly sensitive detection method (potential drop, acoustic emission).

More difficult, however, is the determination of crack initiation toughness for impact loading. The most common test technique to estimate dynamic fracture toughness parameters is the instrumented precracked Charpy (IPC) test (1 - 4). Presently, this test is preferably used to determine K_{Id}- or K_{deff}-values according to the LEFM-concept (5, 6), although there are some difficulties both in analytical and experimental aspects.

In connection with the application of high-toughness steels (for instance for high pressure vessels) it is necessary to expand this test technique in the upper shelf region, this means the determination of elastic-plastic fracture toughness parameters, especially the dynamic R-curve and crack initiation toughness J_{di} (Table 1). Following methods are under discussion:

- multiple specimen methods (stop block (7) or low blow (8, 9))
- single specimen methods (side-grooved specimen (10), key-curve (11), potential drop (12), optical COD measuring (13))
- stretch zone measurement (14).

The objective of this paper is to compare different methods and work out a technical designation for the determination of dynamic crack initiation toughness J_{di}.

TEST PROCEDURE

The tests were carried out on three microalloyed mild steels (Table 2) using Charpy specimens, prefatigued to an a/W-ratio of 0.5. The fatigue cracks were produced by an apparatus working as a mechanical oscillator (15). The resonance vibration period is influenced by the compliance of the specimen. Since the period can be measured with a high accuracy, small variations in crack length are detectable. In this way, it is also possible to produce fatigue cracks with a sharp crack tip and small plastic zones. It could be shown, that for a plastic zone radius between 45 and 365 µm no significant influence on the dynamic R-curve exists (16).

For impact testing an instrumented pendulum was used, equipped with a strain gauge on the tup, and an optical deflection measuring system. The load versus time or deflection signals were stored by an oscilloscope. By using different drop heights or mass pieces the pendulum energy could be varied, and thus different amounts of crack tip blunting and stable crack growth were produced on each specimen (low blow method). A special stop block device was used to limit specimen deflection.

From the load-deflection records the J-integral was calculated by

$$J = \frac{2\ A_i}{10(10-a)} \tag{1}$$

A_i = integrated area

a = notch (2 mm) plus fatigue crack length

Because the low blow method consumes the stored potential energy of the pendulum for crack initiation and limited stable crack growth, a good agreement between the values A_i by integrating the load-deflection curve and by dial reading was reached. This offers a simple way of determing a dynamic blunting line and R-curve without an instrumented pendulum.

All tests were performed at room temperature. After impact loading the unbroken specimens were marked by heat tinting and finally broken into liquid nitrogen. Then the fracture surfaces were examined by a scanning microscope to estimate the stretch zone width. The maximum stretch zone width $(SZW)_c$ was defined as the SZW above which stable crack growth occurs. The stable crack growth was evaluated by measuring the fracture surfaces at 9 equally spaced points along the crack front.

TEST RESULTS

The dynamic R-curve for steel A is shown in Figure 1. It can be seen that the results from different methods are within one scatterband. The experimental blunting line rising factor

$$\beta = J/\sigma_{fld} \cdot \Delta a \qquad (2)$$

$$\sigma_{fld} = \frac{1}{2} R_{ed}(1 + \frac{R_m}{R_{eH}}) \qquad (3)$$

is 3.3 to 4.4 (Table 3).
The R-curves (power law fit) of the 3 steels tested are given in Figure 2. Following possibilities to determine a J_{di}-value were examined (Table 3):

- intersection between R-curve (straight line fit) and blunting line (I)

- point on the R-curve (power law fit) for Δa = 0.1 mm (II)
- point on the R-curve corresponding to $(SZW)_c$ (III).

Since the J_{di}-values from SZ measurement correspond to physical crack initiation, a technical dynamic initiation toughness $J_{d0.1}$ can be proposed as the point on the R-curve for Δa = 0.1 mm.
The examination of the influence of the specimen geometry was performed with varied specimen width and thickness from 7.5, 10 and 15 mm. A significant difference in the J_{di}-values was not provable. By side-grooving up to 32 % the R-curves tend to be flatter because of the change of constraint, but the influence on initiation toughness is very small.
However, it seems to be necessary to make a restriction in stable crack growth to $\Delta a \leq 0.1\ (W-a)$ = 0.5 mm avoiding a violation of the conditions for J-controlled crack growth in the IPC test. Investigations for the application of the key-curve or other single specimen methods have not been finished.

SYMBOLS USED

A_i	=	energy for stable crack growth initiation
a	=	crack length
CVN	=	Charpy-V-notch toughness
J	=	J-integral
J_{di}	=	dynamic J-integral for physical crack initiation
$J_{d0.1}$	=	dynamic J-integral for Δa = 0.1 mm

R_{eH} = upper yield strength

R_{ed} = dynamic yield strength

R_m = tensile strength

SZW = stretch zone width

$(SZW)_c$ = critical stretch zone width

W = specimen width

β = blunting line rising factor

Δa = rate of stable crack growth

σ_{fld} = dynamic flow stress

REFERENCES

(1) Blumenauer H. and Pusch, G., "Technische Bruchmechanik", Deutscher Verlag für Grundstoff-industrie, Leipzig, 1981

(2) Wullaert, R.A. (ed.), "Instrumented Precracked Charpy Testing", EPRI-Meeting, Palo Alto, Dec. 1980

(3) Kalthoff, J.F. and Reisch, A.P.,"Instrumentierter Kerbschlagbiegeversuch zur Ermittlung bruchmechanischer Kennwerte", Tagung Werkstoffprüfung, Bad Nauheim, Dec. 1984

(4) Ortmann, R. and Man, J., Neue Hütte, Vol. 30, 1985, No.6, pp. 233-238

(5) Proposed Standard Method of Test for Instrumented Impact Testing of Precracked Charpy Specimens of Metallic Materials, ASTM-E 24.03.03, Draft 2c, 1980

(6) Man, J., Holzmann, M. and Vlach, B., Comecon-Doc. 0.6 C-12-UFM-6-85, Brno, 1985

(7) Kobayashi, T., Eng. Fract. Mech., Vol. 19, 1984, 1, pp. 49-65

(8) Holzmann, M., Man, J. and Vlach, B., Techn. Mat. RGW 1-13.12, Malacky, CSSR, Nov. 1979, pp. 160-172

(9) Angelino, G. and Fossati, C., in: Proc. ICF 5, Cannes 1981, Vol. 5, pp. 2345-2352

(10) Server, W.L., Wullaert, R.A. and Ritchie, R.O., Trans. ASME, Vol. 102, April 1980, pp. 192-199

(11) Hesse, W., Brüninghaus, K. and Dahl, W., in: Proc. 11. MPA Seminar, Stuttgart, Oct. 1985, Vol. 1, paper 8

(12) Loibnegger, F., Salzmann, F. and Varga, T., in: Proc. 11. MPA Seminar, Stuttgart, Oct. 1985, Vol. 1, paper 5

(13) Rintamaa, R., Scario, T. and Wallin, K., in: Proc. ECF 5, Lisbon, Sept. 1984

(14) Blumenauer, H. and Wagner, I., in: Proc. ICF 6, New Delhi, Dec. 1984, Vol. 5, pp. 3145-3149

(15) Schlät, F., Int. J. Fract., Vol. 19, 1982, R 37 - R 40

(16) Zerbst, U., Thesis A, TH Magdeburg, 1986

TABLE 1 - Application of the IPC test in fracture mechanics

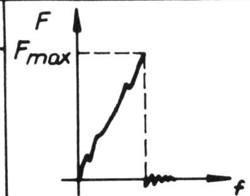
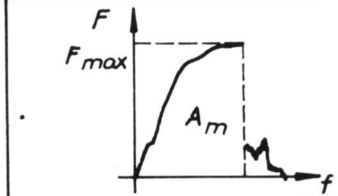
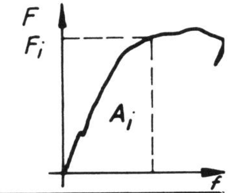
	LEFM	LEFM / EPFM	EPFM
load-deflection record (F - f)			
fracture toughness parameter	$K_{Id} = \frac{F_{max} \cdot S}{B \cdot W^{3/2}} f\left(\frac{a}{W}\right)$	$K_{deff} = \frac{F_{max} \cdot S}{B \cdot W^{3/2}} f\left(\frac{a_{eff}}{W}\right)$ $a_{eff} = a + r_{pl}$ or $J_{dc} = \frac{2 \cdot A_m}{B(W-a)}$ $K_{Id}^{J} = \left(\frac{J_{dc} \cdot E}{(1-\nu^2)}\right)^{1/2}$	$J_d - \Delta a$ - curve $J_{di} = \frac{2A_i}{B(W-a)}$
requirements of the ASTM - and Comecon - standards, see (5) and (6)	$t_f \geq 3\tau$ $a, B, W-a \geq 2{,}5\left(\frac{K_{ad}}{R_{ed}}\right)^2$ $A_o \geq 3A_m$	$t_{GY} \geq 3\tau$ $a_{eff} \geq W$ $a, B, (W-a) \geq 0{,}4\left(\frac{K_{deff}}{R_{ed}}\right)$ $B \geq 25\left(\frac{J_{dc}}{\delta_{fld}}\right)$ $A_o \geq 3A_m$	no standard available
fracture mechanism	unstable crack growth (lower shelf region)	unstable crack growth (transition range)	stable crack growth (upper shelf region)

TABLE 2 - Chemical composition and mechanical properties of the steels tested

steel	C	Mn		R_{eH}	R_m	CVN(+20°C)
		in %		in MPa		in Jcm^{-2}
A	0.09	1.54	0.02 Nb	384	504	221
B	0.16	1.36	0.04 Al	354	531	105
C	0.12	1.58	0.13 V 0.62 Ni	502	616	96

TABLE 3 - Test Results

	J_{di} in Nmm^{-1} determined by method			β	$(SZW)_c$
steel	I	II	III		in μm
A	220	205	165	4.4	73
B	210	200	165	4.4	70
C	295	165	160	3.3	96

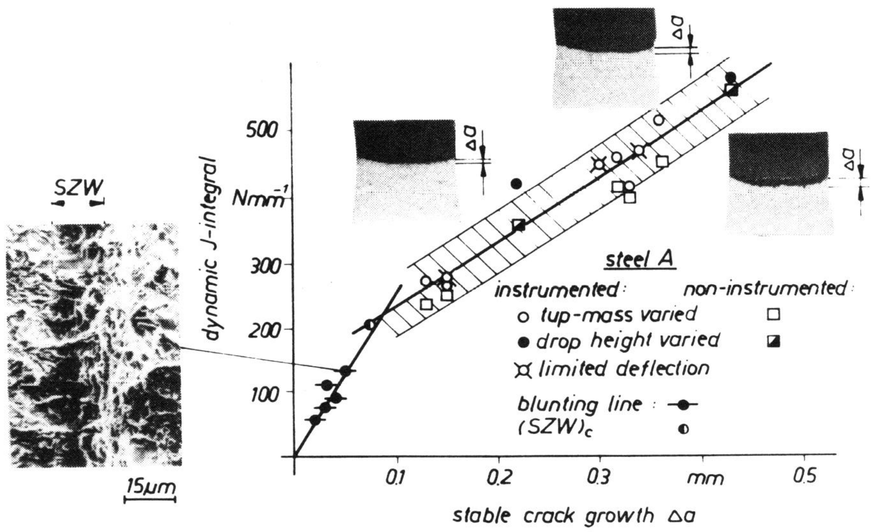


Figure 1 Dynamic R-curve of steel A

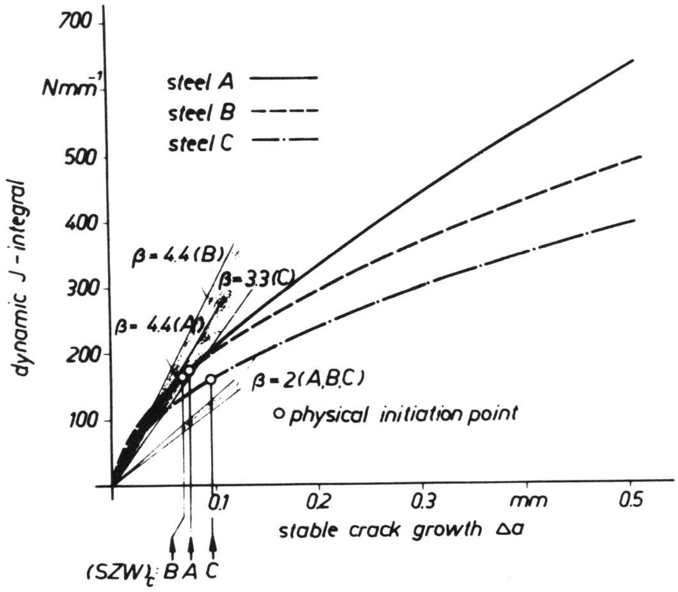


Figure 2 Dynamic R-curves of tested steels