DYNAMIC FRACTURE TOUGHNESS DETERMINATION OF DUCTILE STEELS BY THE INSTRUMENTED CHARPY TEST

H. Blumenauer, R. Ortmann*

A comparison between different methods to determine the resistance curve J_d-Δa and the crack initiation toughness J_{di} by the instrumented Charpy test has been made. It can be concluded, that this rapid and inexpensive test is a suitable alternative to the standard practice using statically loaded specimens, especially in quality control, surveillance and failure analysis.

INTRODUCTION

Recently the R-curve (J-Δa) approach has been widely used to characterize the resistance to crack initiation and crack growth of ductile materials in the upper shelf region (1). The evaluation of a dynamic R-curve by the instrumented precracked Charpy test (2-4) requires the correlation between J_d, calculated from the load-deflection diagram, and the stable crack growth Δa, measured on the fracture surface. To detect the crack initiation point single or multiple specimens techniques are possible. The comparison between several proposals for determining the R-curve and

* Department of Material Engineering, Magdeburg Technical University "Otto von Guericke"/G.D.R.

crack initiation toughness J_{di} is essential for the standardization of this method as an elastic-plastic fracture mechanics test.

TEST REQUIREMENTS AND MATERIALS

Tests were carried out on specimens of two HSLA-steels in L-T- and T-L-orientation. The steel St460 was used on two different upper shelf toughness levels (Table 1).

TABLE 1 - Mechanical Properties (T-L-Orientation)

steel	R_{eH} MPa	R_m MPa	A_5 %	Z %	KCV2 Jcm^{-2} (20°C)	$T_{ü34}$ °C	NDT °C	K_{Id} $MPam^{1/2}$ (-100°C)
St355	405	523	33	74	150	-90	-65	32
St460 (1)	454	715	22	47	70	-40	-30	41
St460 (2)	502	616	28	63	100	-80	-60	46

The V-notch Charpy specimens have been precracked to an a/W-ratio ≈ 0.5; after that some specimens were side-grooved. Fatigue precracking was made according to ASTM-E 399 by a resonance vibration system Dynacomp (5) on a low stress intensity level K_{fmax} = 14 $MPam^{1/2}$, resulting in a small plastic zone and an accurate sharp fatigue crack tip.
The block diagram of the computer-aided instrumented impact tester is shown in Figure 1. Load and deflection data were stored by an 8bit-transient recorder and analyzed by a microcomputer.

Two methods, both with reduced impact velocity, have been used for determining different stable crack extension Δa:

1. Low blow by variation of the drop angles (pendulum velocity $v_o = 0.1...1\ ms^{-1}$)
2. Stop block ($v_o = 2\ ms^{-1}$) using a special device (Figure 2)

Tests were performed in the blunting region (pendulum stopped in the deflection range from general yield to crack initiation) and up to different amounts of stable crack growth. Specimens were heated for colour tinting and finally broken at liquid nitrogen temperature. The fatigue crack length a_o and the stable crack growth Δa were estimated by a microscope according to ASTM-E 813-81; stretch zone width SZW was also measured by a scanning microscope.

The energy integral J_d has been calculated from the absorbed energy obtained by graphical or numerical integration of the load-deflection curve by the equation

$$J_d = \left[\frac{2A_{pl}}{B(W-a_o)} + \frac{F_s^2\ Y(\frac{a}{W})^2\ (1-\nu^2)}{B^2\ W\ E}\right] \cdot \frac{W-a_1}{W-a_o} \qquad (1)$$

The R-curve could be evaluated by a power law approximation. From the condition $\Delta a_{max} \leqq 0.1\ (W-a_o)$ the upper limit of stable crack growth in the J_d-Δa-curve must be fixed at $\Delta a_{max} = 0.5$ mm. To obtain the crack initiation load, which exists prior to the maximum in the load-deflection curve, several single and multiple specimens methods were compared.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The influence of the upper shelf toughness and specimen orientation on the J_d-Δa-curves of the tested steels and a comparison with a static R-curve of the steel St52-3 (6) are seen in Figure 3. Only in a small blunting region the curves are linear; the experimental rising factor for these steels is greater than 4. Because of the formation of many voids and microcracks at the MnS-inclusions in crack tip vicinity the curves are declining before $(SZW)_i$ is reached. As "physically defined" crack initiation toughness J_{di} the point on the R-curve for the critical stretch zone width $(SZW)_i$ can be proposed, because at this moment the crack extends over the whole fatigue crack tip (7). These J_{di}-values obtained from the stop block and the low blow method differ between 178 to 215 Nmm^{-1} because of the reduced potential energy of the pendulum at low blow.

Based on this reference scatter band the obtained values from several single specimens methods can be compared (Figure 4):

a) potential drop (8)
b) key curve (9)
c) step in the logF-logf-plot (10)
d) optical $(COD)_i$ by Rintamaa[1)] (11)
e) based on $(SZW)_i$ by Cornec et al (12)
f) dynamic compliance changing rate by Kobayashi (13)
g) $F_i = F_m$ using side-grooved specimen (14)
h) $F_i = F_m$ without side grooves

1) Authors wish to thank Dr. Rintamaa for conducting this investigation

The validity of the methods a) to g) within the scatter band resulting from the multiple specimens low blow and stop block techniques can be confirmed, but for practical applications it is to be taken into consideration, that the methods a) and d) require an additional instrumentation, method b) based on a numerical analysis and method f) can be carried out only in a computer-aided way.

In Table 2 the values J_{di} and T_d^J (Δa = 0.5 mm) are listed. Under the condition that $(SZW)_i$ is nearby 0.1 mm, an "engineering" crack initiation toughness $J_{d0.1}$ can be used.

TABLE 2 - Crack Initiation Toughness and Tearing Modulus

steel		$J_{di}(SZW)_i$ Nmm^{-1}	$J_{d0.1}$ Nmm^{-1}	T_d^J (Δa = 0.5 mm)
St355	L-T	230	215	777
	T-L	215	235	320
St460(1)	L-T	210	235	432
	T-L	125	170	170
St460(2)	L-T	269	235	440
	T-L	178	235	142
St52-3CaSi 1CT 20%sg (from (6))		280	177	794

CONCLUSION

The instrumented precracked Charpy test is well established as a rapid and inexpensive test for the evaluation of crack resistance curves and crack initiation toughness using small specimens. Combined with stretch zone measurements a physically defined J_{di}-value can be estimated by the multiple specimen technique as well as by more or less sophisticated single specimen methods. The test can be useful in quality control and for the investigation of damaged materials, especially for nuclear reactor materials surveillance.

SYMBOLS USED

A_{pl} = plastic deformation energy (Nmm)
a_o = notch depth + fatigue crack length (mm)
a_1 = actual crack length (mm)
Δa = $a_1 - a_o$ stable crack growth (mm)
B = specimen thickness (mm)
F_i = crack initiation load (N)
F_m = maximum load (N)
F_s = stop load (N)
J_d = dynamic energy integral (Nmm^{-1})
J_{di} = dynamic crack initiation toughness (Nmm^{-1})
W = specimen width (mm)
$Y(\frac{a}{W})$ = geometry correction function

REFERENCES

(1) Schwalbe, K.-H., Neale, B.K. and Ingham, T., Proc. ECF6, Amsterdam 1986, Vol.1, pp. 277-286

(2) Blumenauer, H. and Ortmann, R., Proc. ECF6, Amsterdam 1986, Vol.1, pp. 441-450

(3) Kobayashi, T., Eng. Fract. Mech., Vol.9, No.1, 1984, pp. 49-65

(4) Aurich, D., (ed.), BAM-Forschungsbericht 137, Berlin, 1987

(5) Schlät, F., Int. J. Fract., Vol.27, 1982, pp. R 37-40

(6) Sun, D.-Z., Halim, A. and Dahl, W., 19. Arbeitskreis Bruchvorgänge im DVM, Freiburg, 1987

(7) Blumenauer, H., Wagner, I. and Schröder, M., 20. Arbeitskreis Bruchvorgänge im DVM, Frankfurt, 1988

(8) Loibnegger, F., Salzmann, F. and Varga, T., 11. MPA-Seminar, Stuttgart, 1985, Vol.1, Vortrag 5

(9) Brüninghaus, K., Hesse, W., Twickler, M. and Dahl, W., J. de Physique 46, 1985, C5, pp. 227-232

(10) Krüger, G. and Löbner, W., Neue Hütte 24, 1979, No.5, pp. 180-182

(11) Rintamaa, R., Saario, T. and Wallin, K., Proc. ECF5, Lisboa, 1984, Vol.II, pp. 961-972

(12) Cornec, A., Heerens, J. and Schwalbe, K.-H., 18. Arbeitskreis Bruchvorgänge im DVM, Aachen, 1986

(13) Kobayashi, T., Yamamoto, I. and Niinomi, M., Eng. Fract. Mech., Vol.24, 1986, No.5, pp. 773-782

(14) Server, W.L., Wullaert, R.A. and Ritchie, R.O., Trans. ASME, J. Eng. Mat. and Techn. 102, 1980, No.6, pp. 192-199

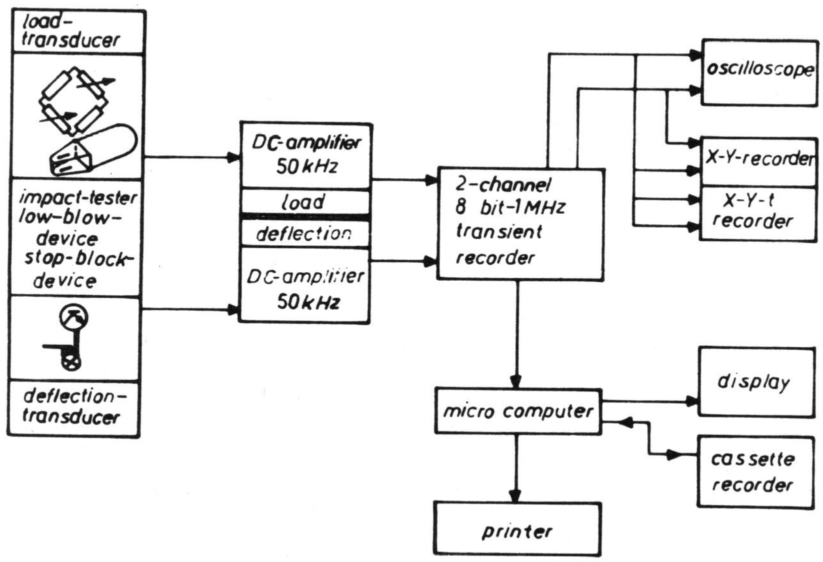

Figure 1 Block diagram of the instrumented Charpy tester

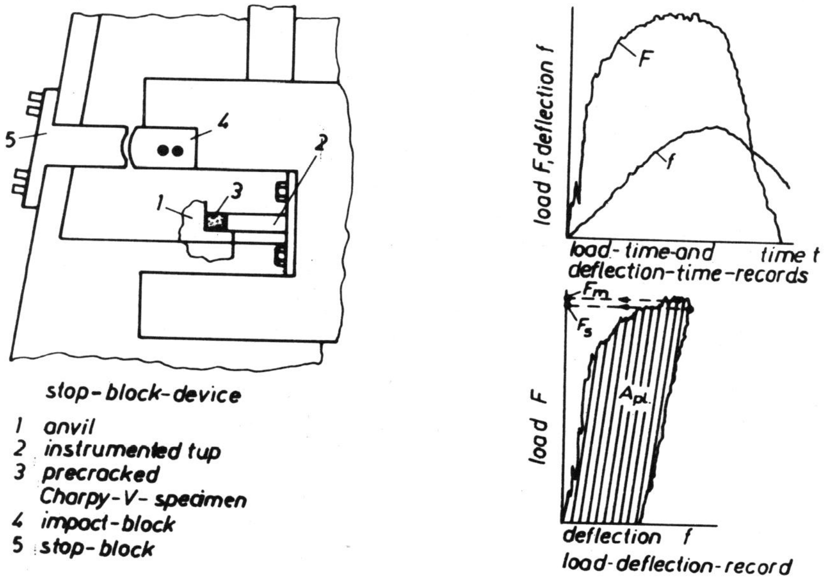

Figure 2 Stop block device and plotted test records

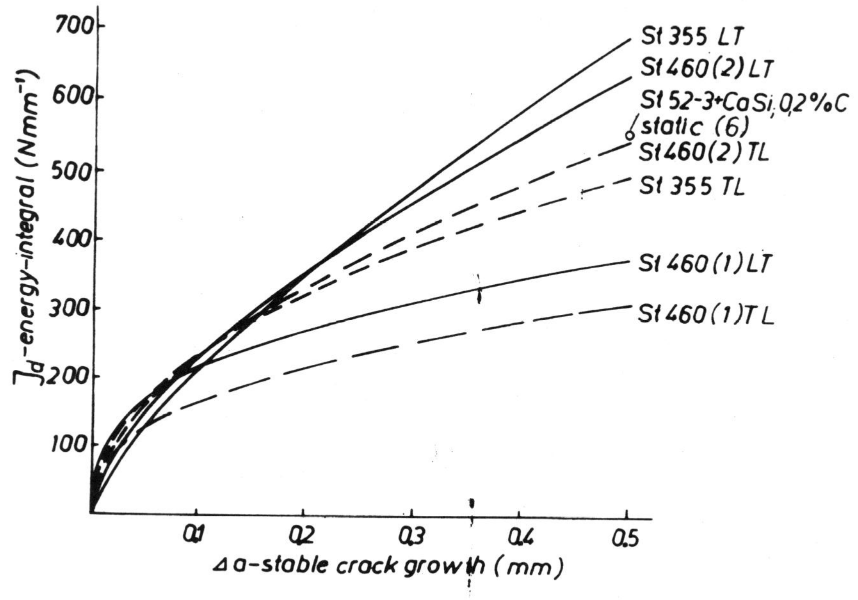

Figure 3 J_d-Δa-curves

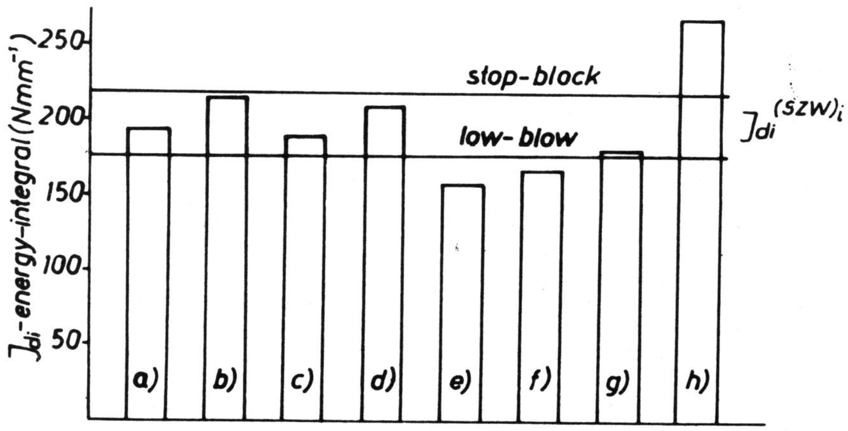

Figure 4 Crack initiation toughness J_{di} (steel St460(2))