EXPERIMENTAL DETERMINATION OF CRACK GROWTH RESISTANCE CURVES

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The single specimen partial unloading compliance and the direct current potential drop method are used to generate crack growth resistance curves and to deduce initiation toughness values for material characterization and component safety assessment. The advantages and deficiencies of both methods are compared and influences of details of the experimentation and the evaluation are demonstrated on the basis of results for different structural steels at room and elevated temperature. Problems with the application of the ASTM-J_{Ic}-standard and possible improvements are discussed.

INTRODUCTION

Crack growth resistance curves in terms of the elastic plastic parameter J are used to assess the safety of components with cracks against initiation of stable growth and ductile instability. ASTM provides a standard to determine the initiation tougness J_{Ic} (1) and proposes a rule for a material resistance curve $J_R(\Delta a)$ (2). The reliability and accuracy of these methods are a necessary basis of ongoing research into the problem of a unique i.e. a geometry independent material characterization and of transferability of the results onto structural behavior. Some of the chances and problems in the experimental determination of crack growth resistance curves are described in this paper.

MEASUREMENT PROCEDURES

To generate a crack growth resistance curve a crack driving parameter, for instance J, and the corresponding stable crack growth Δa have to be measured. Following the standard ASTM E 813-81 (1) J may be evaluated from the work done on the cracked specimen of interest and the crack lengths are derived from direct measurements on the fracture surfaces of a series of separate specimens (see Fig. 1). Improved techniques are now available to derive the same kind and extent of information from single specimen tests.

Single specimen partial unloading compliance method (SSPUC)

Instead of using the interrupted loading technique the increasing crack length can be assessed from successive measurements of the elastic compliance C of the specimen which is derived from relatively small superimposed unloadings and known functions a = f (C, E, specimen geometry) - see Fig. 1. Meeting the standard conditions of (1) for the number of data points (unloadings) and

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appropriate data grouping a J_{Ic}-value is determined by extrapolation which - in a technical sense - characterizes initiation for each specimen; additional statistical information is then gained by testing several specimens.

The major problems with the SSPUC method are the requirement of a very high accuracy, stability, and linearity of all components of the measurement and data acquisition system and of a low-friction loading device. Fig. 3 demonstrates the quality of results which are obtained by the latest version of the IWM-system. Especially no more hysteresis and apparent negative crack growth is observed as described in (3). The evaluation in Fig. 3 has followed the line given in (2) including crack growth correction for J (4). The intersection of the formal blunting line $J = 2 \cdot \sigma_F \cdot \Delta a$ - which in this case is well described by the first 5 to 6 data points - with a regression line through selected "valid" data points defines J_{Ic} according to (1).

The experiment documented in Fig. 3 has been numerically evaluated by Schmitt et al. (5).

Direct current potential drop method (DCPD)

The principle of the method as described by Kloss (6) is shown in Fig. 2. Fig. 4 shows an example of a force versus opening displacement diagram including the expanded part of the potential drop at a constant current of 5 Amps. The change in slope labeled "i" is normally thought to be caused by initiation of stable crack growth. But because of not well understood additional effects of elastic and plastic deformations the exact point of initiation should be confirmed by a second specimen unloaded just beyond the assumed initiation and by subsequent fractographic examination.

If the initiation value and the amount of stable crack growth from one interrupted loading test are known a J-resistance curve can be constructed by linear interpolation. In Fig. 5 from (6) a good correlation is found between an interrupted loading test series and a J-R-curve derived from a potential drop measurement. The J_{Ic}-value defined according to ASTM (1) by an extrapolation to $\Delta a = 0$ of the regression line through four data points between $0{,}15 \leq \Delta a \leq 1{,}5$ mm is about 12 % greater than the J_i value calculated for the displacement at "i" in Fig. 4, which is well confirmed by the first interrupted loading point. The ASTM procedure yields a critical J value beyond onset of real physical crack growth.

RESULTS - INFLUENCE OF EXPERIMENTATION AND EVALUATION

The methods used to determine J-R-curves, details of the experimentation and of the evaluation procedure may well influence results derived from an elastic plastic $J-\Delta a$ test. Some examples will be given in the following sections.

Comparison of SSPUC and DCPD

Figs. 6 and 7 show results from a partial unloading experiment with simultaneous measurement of potential drop (for clarity the φ-data during unloading have been eliminated in Fig. 6). For this comparison a critical opening displacement of V = 0.55 mm for first real crack growth after crack tip blunting (between points 5 and 6) was read from the compliance measurements and was then used to define the initiation value of the PD-curve; the second PD-calibration point was adjusted to the crack length measured by partial unloading.

Both methods deliver similar J-R-curves. But the interrupted loading points as well as the partial unloading data in Fig. 5 fall below the respective

PD-J-R-curves. This difference may be due to non linear effects at onset of crack growth not taken account of by the simple interpolation procedure. The distinct change in slope after about 1.5 mm of stable crack growth is a consequence of crack front tunneling, causing underestimation of crack growth by both methods.

Data grouping conditions

To avoid errors in J_{Ic} by regression through clustered data points the ASTM standard (1) sets some requirements for valid data. Points no. 15 to 38 in Fig. 8 are the valid points of this experiment. Assuming that some of these points were not measured limiting cases of acceptably grouped data points are no. 15 to 24 and no. 22 to 38. Respective ASTM J_{Ic}-values are 95 kJ/m^2 and 140 kJ/m^2 instead of 117 kJ/m^2 for the complete set of data. Obviously these systematic errors are caused by drawing a straight line through data points on a curve. Requiring a minimum regression coefficient cannot delete this error, all three values of this example being better than .994. At least one data point close to the .15 mm-offset line should be required.

Alternatively, Loss et al. (7) propose to fit a power law function to the valid data points and to determine J_{Ic} (for data as in Fig. 8) at the intersection of this curve with the .15 mm-offset line. This definition has proved to be equivalent within experimental accuracy for normal experiments. But it is much less sensitive to the data grouping as discussed before. Nevertheless, at least one data point near to the .15 mm-offset line should be required.

Initial crack length measurement

The standard excludes points left of the .15 mm-offset line for evaluation, thereby excluding part of the error resulting from scatter for small Δa-values. But especially for experiments at elevated temperature an uncertainty in the initial crack length measurement must be considered. Fig. 9 shows a J-R-curve measured at 300°C with a visible amount of scatter in Δa. Reevaluating the data with initial crack lengths differing by only ± .05 mm (.2 %) from the measured mean value a_o yields J_{Ic}-values within a range of about 18 %. In contrast to the consideration of the preceding section both definitions, ASTM and Loss, are comparably sensitive.

Compared with the big change in J_{Ic} the small shift of the J-R-curve would be nearly invisible and is not plotted in Fig. 9.

Side grooves

Specimens with smooth surfaces as normally used for fracture mechanics experiments reveal preferential crack growth in the middle of the specimens (tunneling). To avoid the underestimation of crack length from compliance measurement caused by tunneling the standard proposes side grooves of about 20 % of specimen thickness. For such specimens the J-values along the crack front through the thickness are more homogeneous (deLorenzi and Shih (8)) thereby causing nearly parallel crack extension instead of tunneling. Fig. 10 shows nearly zero difference for the 20 % side grooved specimen between predicted and measured crack length (filled circle) and an underestimation of a for the smooth specimen. But even after stretching the J- a-values to meet the measured last point there remains a difference in the slopes of the resulting curves. The stress state at the crack tip of the side grooved specimen is close to plane strain (5) resulting in a lower J-R-curve. In contrast both extrapolated J_{Ic}-values are well within the scatterband of this material.

Number of unloadings

Each unloading in a partial unloading experiment may be considered as one fatigue load cycle possibly causing additional crack growth. Fig. 11 demonstrates that there is only little if any effect of the 10 % elastic unloading on the J-resistance curve. During this experiment the step between two unloadings was increased once at limit load. Both branches of the curve may be joined by a smooth curve and a comparable specimen of the same series interpolates perfectly the gap.

Up to now for different materials no evidence of a significant effect of the number of unloadings on the J-R-curve has been found. Therefore it is recommended to measure many more data points in the regression region than required by the standard (1) to get a more reliable J_{Ic}-extrapolation.

Variation of resistance along the crack path

Fig. 12 shows the diagrams of one experiment where locally low crack resistance may have caused small crack jumps and related load drops (marked by arrows). Work is in progress to investigate by FE-simulation (as discussed in (5)) the mechanical part of this effect and to relate it to local variations in microstructure.

CONCLUSIONS

The single specimen partial unloading compliance method (SSPUC) and the direct current potential drop method (DCPD) can both be used to generate crack growth resistance curves and evaluate values of the initiation toughness J_{Ic}. SSPUC delivers an "absolute" curve for each specimen. The quality of such a result can be checked by comparing the predictions for initial and final crack length with measurements on the fracture surfaces. The results of the DCPD-method (as used here) depend on a calibration and interpolation between initial and final crack length and the definition of the initiation point. Therefore, one additional specimen is recommended to confirm the initiation point J_i. The J_{Ic}-value and the J-R-curve are less sensitive to small errors in the definition of initiation.

J_{Ic} determines a critical J-value close to initiation but for a material-dependent small amount of stable crack growth.

Certain deficiencies of the ASTM standard for J_{Ic} determination (1) have been pointed out and ways for correction are proposed: To diminish effects of scatter the number of data points should be increased. To avoid systematic errors the data grouping condition should ask for small Δa-values. Frequently the alternative power law regression (7) seems to be more appropriate.

To characterize minor material differences by J_{Ic} high experimental accuracy for well defined data points is necessary. Then the multi-specimen method seems not to be adequate because it suffers from material variations for different specimens. Several single specimen tests on the other hand deliver additional information about this scatter.

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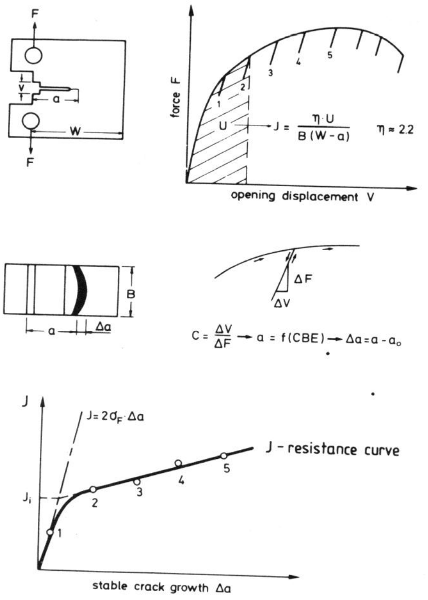


Figure 1 Principle of single specimen partial unloading compliance method (SSPUC)

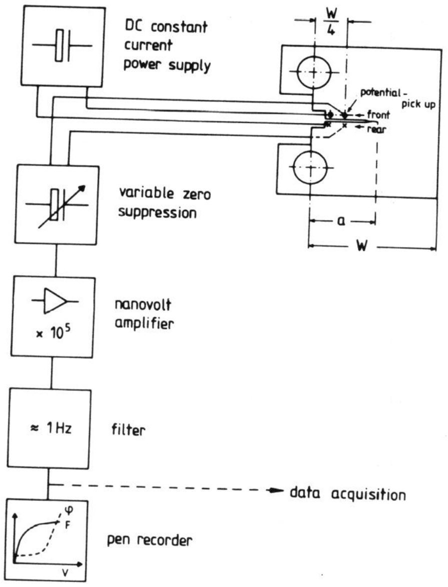


Figure 2 Principle of direct current potential drop measurement (DCPD)

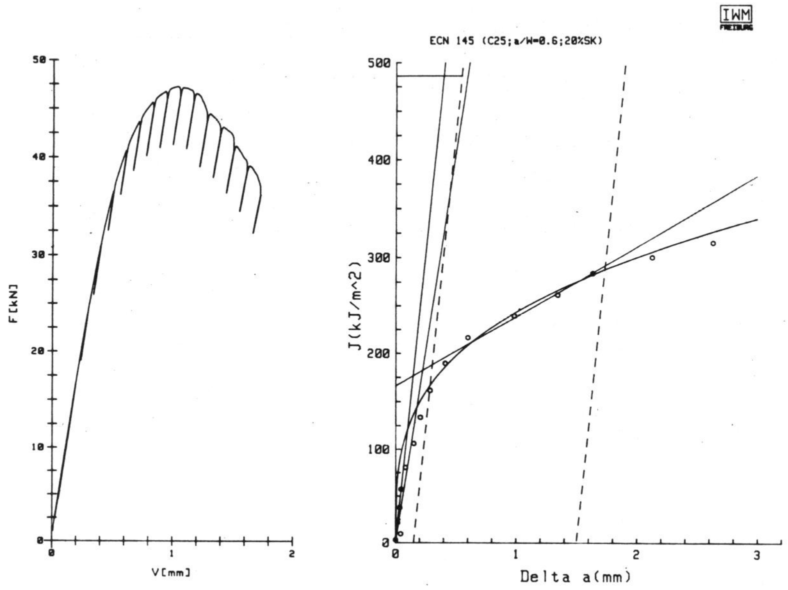


Figure 3 Force (F) vs. displacement (V) diagram and J-R-curve determined by SSPUC

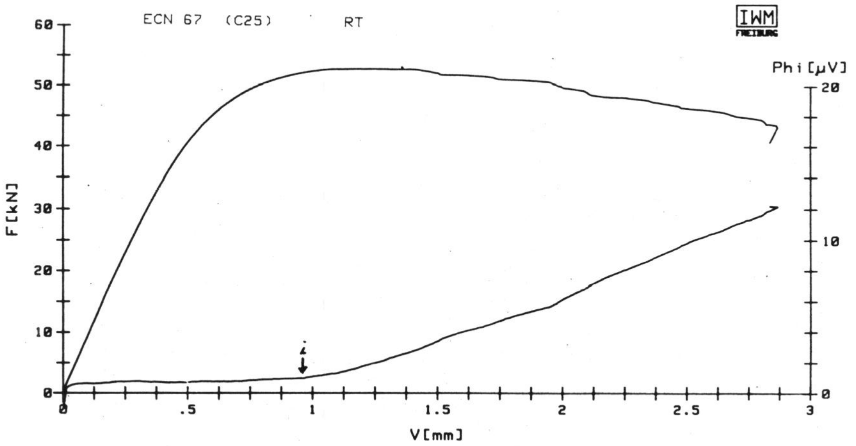


Figure 4 Force (F)/DC potential drop (φ) vs. displacement (V); change in slope at initiation of crack growth "i"

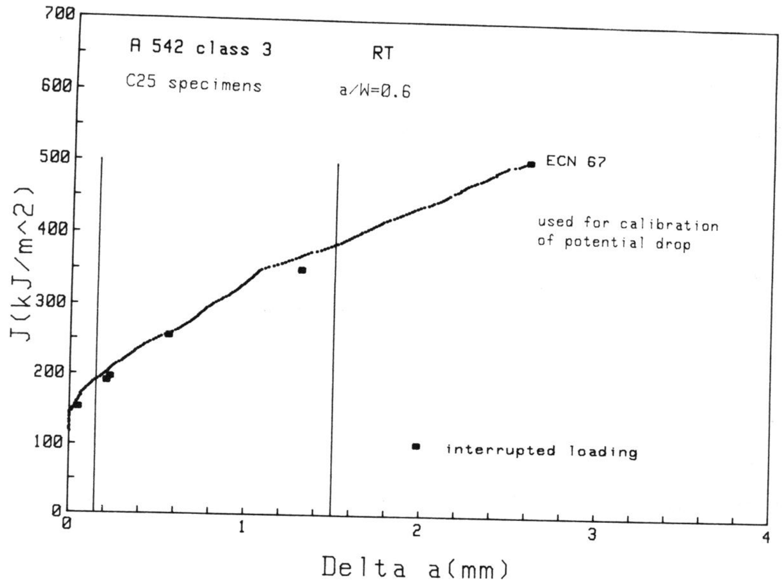


Figure 5 J-R-curve from DCPD measurement - interrupted loading points for comparison

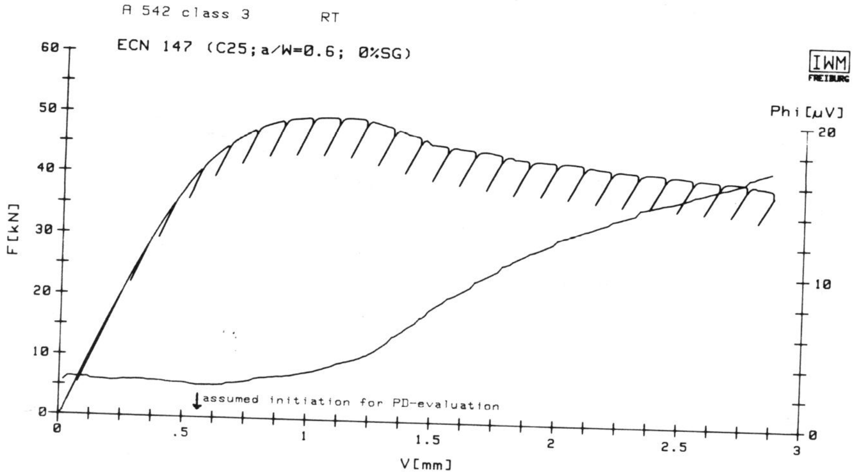


Figure 6 F/φ vs. V diagram of simultaneous SSPUC- and DCPD experiment

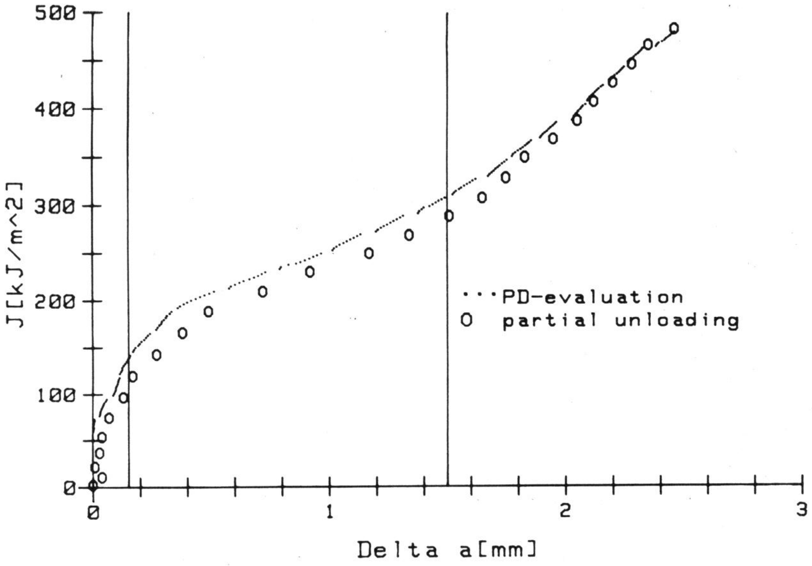
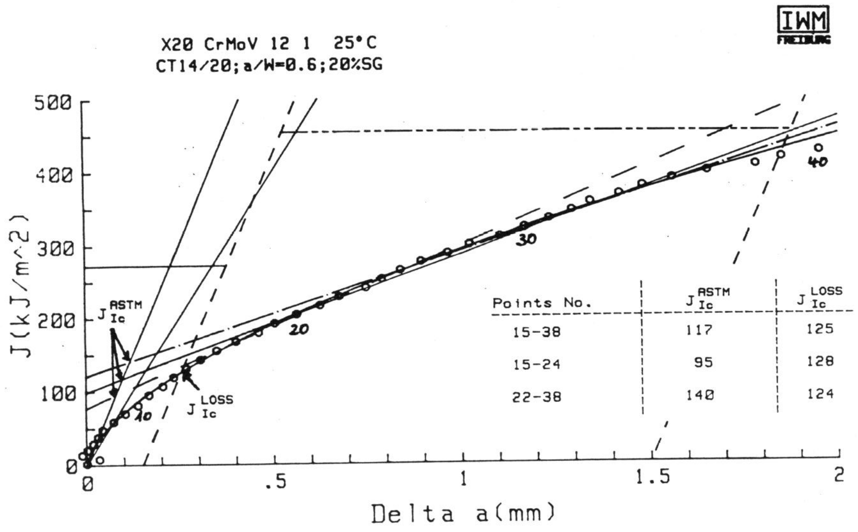


Figure 7 J-R-curves evaluated from SSPUC (Δa including blunting) and DCPD (Δa without blunting, final Δa adjusted)



Points No.	J_{Ic}^{ASTM}	J_{Ic}^{LOSS}
15-38	117	125
15-24	95	128
22-38	140	124

Figure 8 J-R-curve from SSPUC - influence of evaluation on J_{Ic}

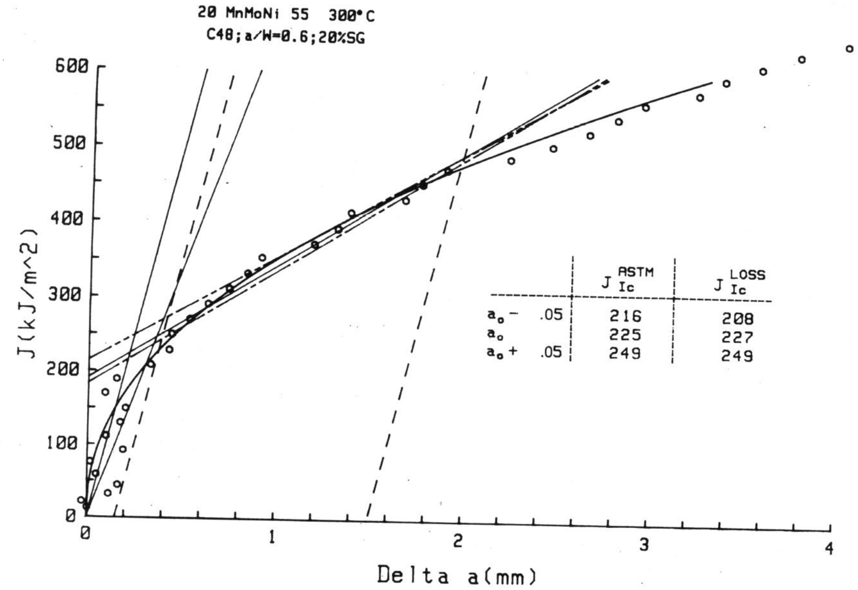


Figure 9 J-R-curve from SSPUC - influence of experimental error of initial crack length estimation

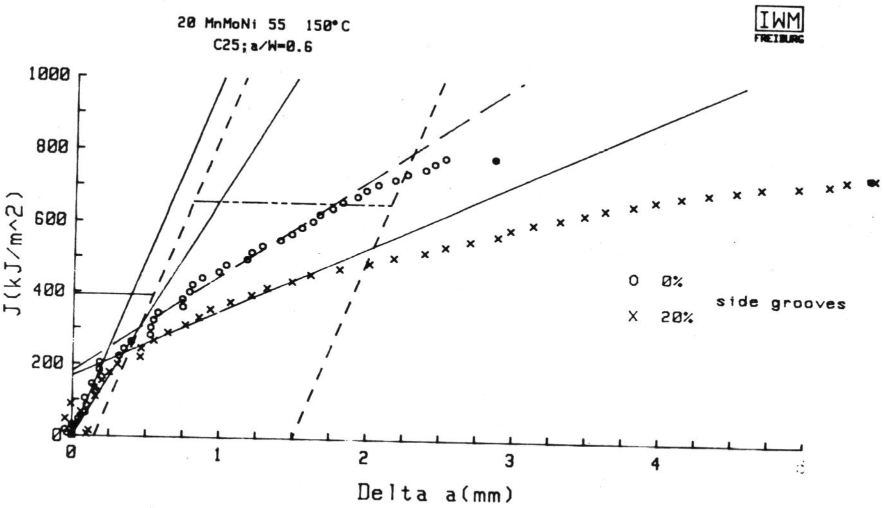


Figure 10 Influence of side grooving on J_{Ic} and J-R-curve (● Δa measured on fracture surface)

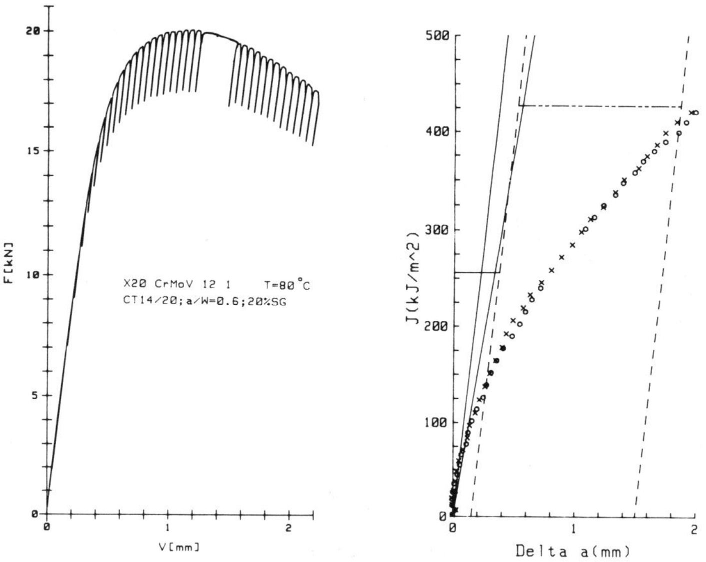


Figure 11 Influence of number of unloadings on resulting J-R-curve

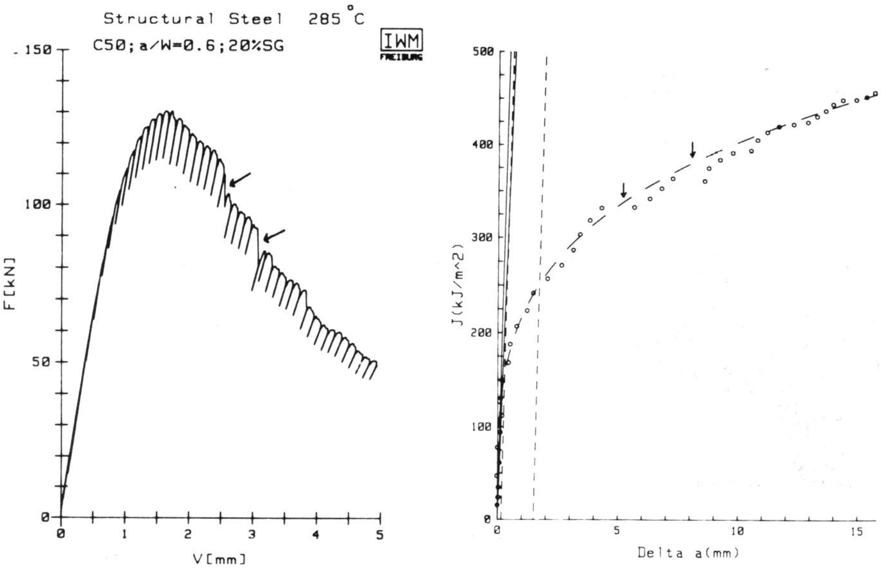


Figure 12 F vs. V diagram with load drops and J-R-curve with corresponding steps in crack growth