PREDICTION OF MAXIMUM LOAD VALUES OF DIFFERENT SIZED CT-SPECIMENS USING THE J-R-CURVE CONCEPT

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To investigate the influence of specimen geometry on the R-curve behaviour of a structural steel St 52-3, fracture mechanics experiments have been carried out on compact tension specimens with variable thickness, width and crack length. J-R-curves were determined by a multiple-specimen-technique. Neglecting second order effects, the J-R-curve was found to be independent of specimen geometry. Using the geometry independent J-R-curve, the maximum load values of the CT-specimens with various sizes were calculated applying the estimation technique developed by Shih and Kumar for evaluating the "crack driving force".

INTRODUCTION

Fracture criteria refering to the onset of stable crack growth often underestimate the true failure load, because they make no use of the reserve in safety due to the rise of crack growth resistance with increasing stable crack extension. The resistance curve (R-curve) concept yields a more reliable estimation of the fracture behaviour.

Originally the R-curve concept was developed for describing stable crack growth under small scale yielding conditions (1). Recently, it has been extended into the elastic-plastic (2,3) and fully plastic regime (4).

It was the purpose of this paper to investigate the influence of specimen geometry on the rise of crack growth resistance with crack extension for large scale plasticity and to predict maximum load values of CT-specimens of various sizes using the R-curve concept.

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EXPERIMENTAL PROCEDURE

Fracture mechanics experiments were carried out on structural steel St 52-3 having a room temperature yield strength of 350 N/mm^2. The tests were conducted on compact tension (CT-) specimens in the upper shelf range at a temperature of -20°C. Standard CT-specimens of different size but constant thickness to width ratio were tested as well as CT-specimens of constant thickness but different widths and crack lengths. The specimen thickness B was varied from 12.5 to 75 mm, the width W from 25 to 200 mm and the crack length to width ratio a/W from 0.3 to 0.75.

The resistance curves were determined by a multiple-specimen-technique. A typical serie of load-displacement curves of 1 CT standard specimens is shown in Fig. 1. The fracture surfaces of CT-specimens loaded to different displacement values, that are indicated by arrows in the load-displacement trace, are shown in the lower part of Fig. 1. The stable crack extension begins near maximum load and the crack grows under large scale plasticity conditions. The arrow on the load axis indicates the plastic limit load F_0 being in good agreement with the maximum load. The stable crack growth was evaluated by measuring the crack extension at 9 equally spaced points along the crack front and averaging to give mean values. The average and maximum stable crack growth values Δa and Δa_{max} are shown as a function of displacement in Fig. 1. The initiation of stable crack growth can approximately be estimated by the extrapolation of the crack extension-displacement curves to $\Delta a = \Delta a_{max} = 0$ (dashed line).

Many delaminations running perpendicular to the main crack area caused a non regular crack front shape. A remarkable crack front tunneling was observed especially in small specimens (see Fig. 2). The R-curves were plotted in terms of J-integral values versus Δa. The J-integral was evaluated according to ASTM E 813. Only for specimens with $a/W < 0,5$ the analysis of Merkle and Corten (7), that accounts for the tension component in the CT-specimen, was used. The J-integral values were not corrected for crack growth, because it was found (8), that for crack extensions Δa smaller than one tenth of the ligament size b the corrected J-values nearly coincided with the J-values calculated with the original crack length.

THEORETICAL ASPECTS

Hutchinson and Paris (5) showed, that the J-integral can be considered as the relevant crack tip field parameter in certain limits, even if stable crack growth has occured and non proportional loading is dominant at the crack tip. To characterize the crack tip field by the J-integral, the local regions of non proportional loading at the crack tip have to be small against the HRR-field radius, in which there is proportional loading and the J-integral theory is applicable. The theoretical considerations of Hutchinson and Paris have been confirmed by Shih et al. (4,6), who investigated the stable crack growth in compact tension specimens of steel A533B. They found, that J-controlled crack growth is dominant in fully plastic CT-specimens, if the following conditions are fulfilled

$$\begin{aligned} \Delta a &< 0{,}06\ b \\ \omega &= b/J \cdot dJ/da > 10 \\ b &> 25\ J/\sigma_F \\ B &\geq b \end{aligned} \qquad (1)$$

If these conditions are met, the J-R-curves are expected to be geometry independent. Using the geometry independent J-R-curve, it should be possible to predict instability loads of various specimen geometries, if the "crack driving force" is known. In the present paper the "crack driving force" was derived from the estimation technique of Shih et al. (6). According to this technique the J-integral can be determined for a power-law hardening material by

$$J = K^2/E' + \alpha \cdot \sigma_0 \cdot \varepsilon_0 \cdot b \cdot h_1 \cdot (F/F_0)^{N+1} \qquad (2)$$

where α, N, σ_0 and ε_0 are defined by the hardening relation

$$\varepsilon/\varepsilon_0 = \alpha\,(\sigma/\sigma_0)^N \qquad (3)$$

K is the tensile stress intensity factor, E' is Young's modulus and F is the applied load. F_0 is the plastic limit load, which has been derived in (6) on the basis of the work of Merkle and Corten (7). The factor h_1 has been determined by numerical calculations and is tabulated for different geometries and hardening exponents N (6).

RESULTS

The influence of specimen size, width and crack length to width ratio a/W on the J-R-curve is shown in Figures 3, 4, and 5. The J-R-curves of standard CT-specimens with various sizes coincide for small crack elongations (Fig. 3), but at larger Δa-values the R-curves of the larger specimens tend to be steeper. This may be explained by the violation of the conditions (1) for J-controlled crack growth. The severest condition in equation (1) is the crack growth restriction $\Delta a < 0{,}06$ b, which is indicated by arrows on the Δ a-axis. The arrows approximately coincide with the first deviation of the 1/2 CT- and 1 CT-R-curves from the 3 CT-R-curve. But stable crack growth under J-controlled conditions, which are met for 3 CT-specimens over the whole investigated crack extension range, should describe the material behaviour in a conservative way and therefore yield the lowest R-curve (6). This is obviously not the case. Therefore more likely reasons for the slight geometry dependence of the R-curves are the specimen contraction in thickness direction and the remarkable crack front tunneling in the smaller specimens.

J-R-curves of CT-specimens of constant thickness and variable widths (Fig. 4) and crack lengths (Fig. 5) agree very well, although the plane strain condition $B \geq b$ was only fulfilled for the 25 mm thick specimens with $a/W \geq 0.5$. Only the J-R-curve of the CT-specimen with $a/W = 0.3$ deviates from the other curves, because considerable yielding around the pins had occured during crack growth. The plane strain criterion, as given in (6), seems to be too severe. The geometry independence of the J-R-curves is consistent with the conditions (1) for J-controlled crack growth, if $B \geq b$ is replaced by the criterion $B > 25\ J/\sigma_F$, which is fixed in the J_{Ic}-standard ASTM E 813. Then again the crack growth restriction $\Delta a < 0{,}06\ b$ (arrows in Figures 4 and 5) is the severest condition.

The maximum loads of different sized CT-specimens were predicted by using the mean J-R-curve of CT-specimens of different widths (Fig. 4). Figure 6 shows the J-R-curve and "crack driving force" curves calculated for different load levels by equation (2) for a 25 mm thick and 200 mm wide CT-specimen. The arrow marks the instability point, respectively the maximum load, which is attained, when the "crack driving force" curve tangents the J-R-curve. In Figures 7, 8, and 9 the maximum loads, estimated by the J-R-curve concept, are compared with the experimentally determined maximum loads of CT-specimens of various geometries. The "crack driving force" curves were calculated for the plane strain and plane stress case. The measured maximum loads lay between the plane strain and plane stress predictions, because the crack advanced neither in a pure plane strain nor in a pure plane stress state. If the ligaments were large compared with the thickness, the plane stress case yielded a good approximation of the maximum loads.

CONCLUSIONS

Stable crack growth under large scale plasticity has been investigated on CT-specimens with various sizes of steel St52-3. The J-R-curve was found to be widely unaffected by specimen geometry, if certain requirements are met. By using a modified criterion for plane strain crack growth the geometry independence of the J-R-curves is consistent with the conditions (1) developed by Shih et al. (6). The R-curve concept has been successfully applied for predicting instability loads in the fully plastic regime. The experimentally determined maximum loads of CT-specimens with various sizes were conservatively estimated by assuming plane stress behaviour in the evaluation of the "crack driving force".

REFERENCES

1. Heyer, R. H., 1973, ASTM STP 527, 3
2. Kaiser, H.-J., and Hagedorn, K. E., 1980, Proc. ECF 3, 79
3. Kaiser, H.-J., and Hagedorn, K. E., 1981, Proc. ICF 5, 2, 855
4. Shih, C. F., de Lorenzi, H. G., and Andrews, W. R., 1979, ASTM STP 668, 65
5. Hutchinson, J. W., and Paris, P. C., 1979, ASTM STP 668, 37
6. Shih, C. F., German, M. D., and Kumar, V., 1979, "An Engineering Approach for Examining Crack Growth and Stability in Flawed Structures", OECD-CSNI Specialists Meeting, Washington
7. Merkle, J. G., and Corten, H. T., 1974, ASME-Paper No. 74-PVP-33
8. Kaiser, H.-J., 1982, "Untersuchungen zum Einfluß der Probengeometrie auf das stabile Rißwachstum im Bruchmechanikversuch", PhD-Thesis, RWTH Aachen

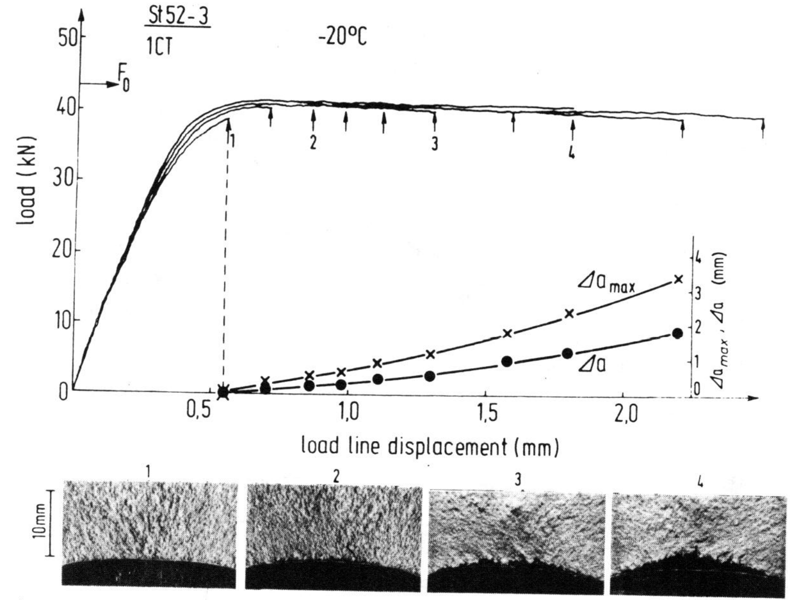

Figure 1 Load-displacement-, crack extension-displacement-curves and fracture surfaces of 1 CT-specimens

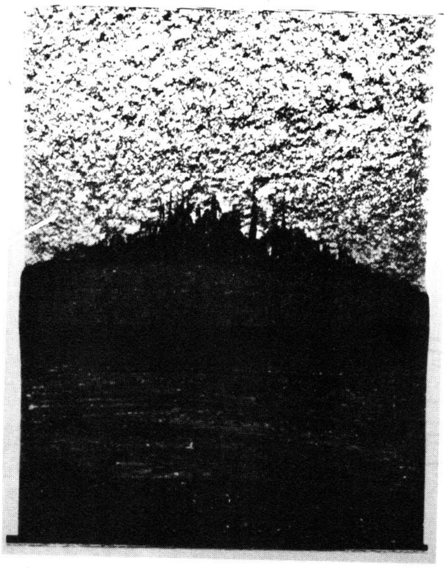

Figure 2 Fracture surface of a 1/2 CT-specimen

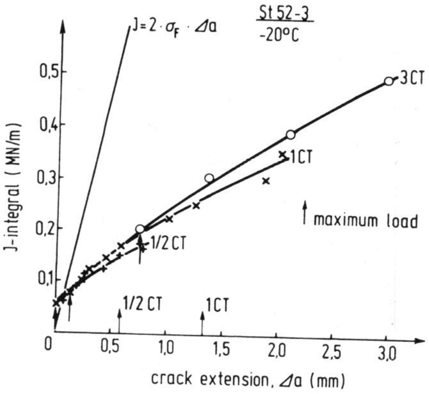

Figure 3 Influence of specimen size on the J-R-curve

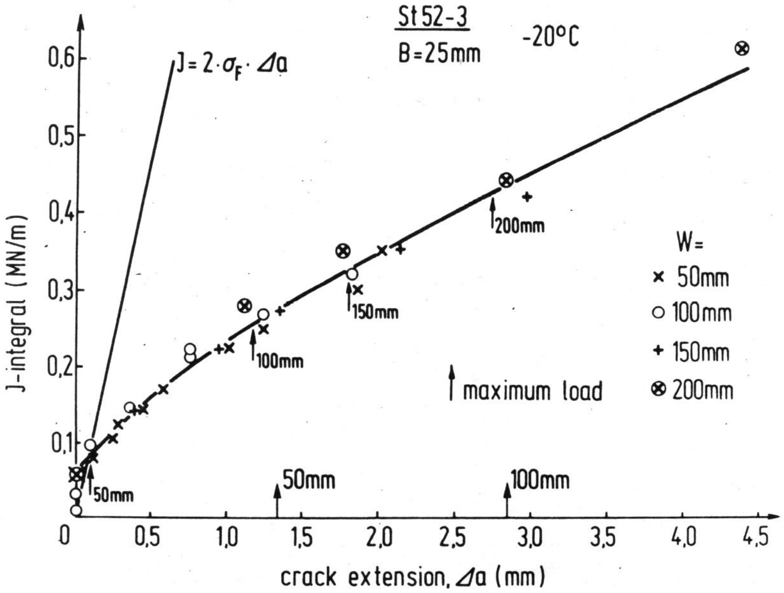

Figure 4 Influence of specimen width W on the J-R-curve

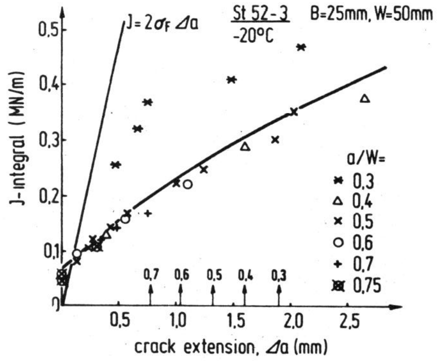

Figure 5 Influence of a/W on the J-R-curve

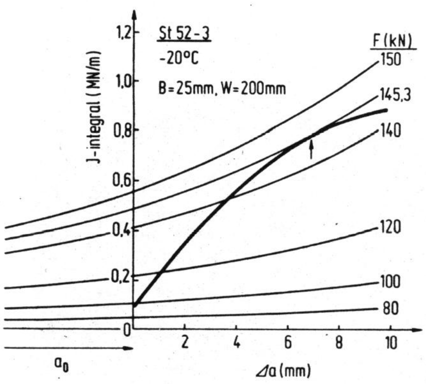

Figure 6 Prediction of instability loads

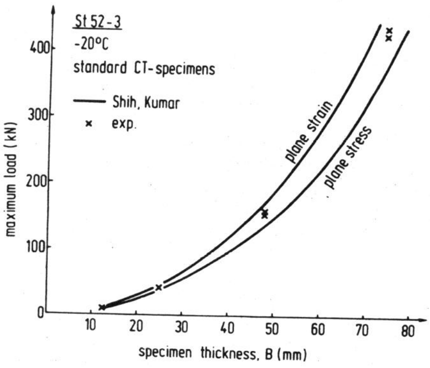

Figure 7 Measured and predicted max. loads for various sizes

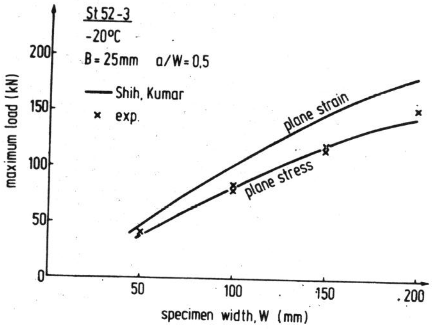

Figure 8 Measured and predicted max. loads for various widths

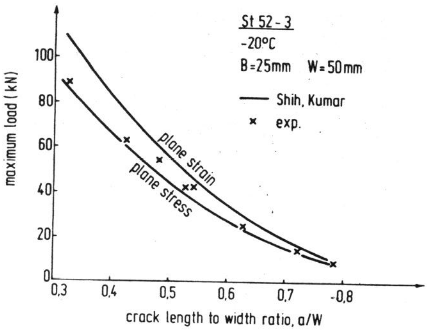

Figure 9 Measured and predicted max. loads for various a/W-ratios