APPLICATION OF THE KEY CURVE METHOD ON STATIC AND DYNAMIC J_R-CURVE DETERMINATION WITH CT- AND SENB-SPECIMENS

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The key curve method was applied to determine J_R-curves of a variety of steels. A brief description of the method is given. It is shown that a key curve function can be obtained by FE-computations and can be normalized by the yield strength, so that it can be used for various materials. The results are compared with those obtained by other methods such as multiple specimen technique and potential drop technique. The method was finally applied to tests at higher displacement rates.

INTRODUCTION

The determination of J_R-curves is usually done by one of the well accepted methods like partial unloading or potential drop technique. The multiple specimen technique is considered as a reference method to compare all other single specimen techniques with. The key curve method proposed by Ernst et al. (1), (2) hasn't yet been used widely for practical applications.

Some authors have published their experiences about the method for example Joyce (3) and Steenkamp et al. (4). In general accurate J_R-curves were obtained showing a reasonable good agreement with results from other crack length measurement techniques. Some advantages of the key curve method are evident, stated in (3), too:

- J_R-curve determination doesn't require any additional instrumentation of the test specimen and can be obtained directly from the load displacement curve
- the method can be applied to high displacement rates as long as an accurate load displacement record can be obtained

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The main problem associated with the key curve method is the determination of a key curve function or calibration function. Basically such a curve can be obtained by numerical computations (finite elements) or by testing subsized specimens (1). For practical applications, however, this way seems to be too complicated for standard testing and suitable only for special cases, like high testing rate.

The aim of this work was to show that the key curve method can be used to obtain accurate J_R-curve agreeing well with results from other techniques. The calibration function normalized to the yield strength was determined by FE-computations and was used for various steels with different yield strengths.

Crack Length Determination Using the Key Curve Method

The method is very similiar to the partial unloading technique. With both methods the instantaneous crack length in terms of a/W is determined from the mechanical load displacement behaviour of the fracture mechanics specimen. Whereas at the partial unloading technique the crack length is derived from the elastic compliance determined by partial unloadings, the crack extension is determined from a single load displacement record. The required calibration curve represents the elastic and plastic load displacement behaviour of a fracture mechanics specimen as a function of crack length:

$$F = f(a, \Delta) \qquad (1)$$

It is obvious that this function depends on the true stress strain curve of the material and on the test piece type. Normalizing load F, crack length a and displacement Δ by the specimens dimensions gives eq. (2), which is independent of the specimen size for geometrical similiar configurations:

$$\frac{F}{BW} = f(a/W, \Delta/W) \qquad (2)$$

According to Ernst et al. (1) bending can be taken into consideration dividing F/BW by b^2/W^2, where b is the ligament size. Hence, eq. (3) represents a a/W-independent calibration curve for the case of pure bending, so for a SENB-specimen:

$$\frac{FW}{Bb^2} = f(a/W, \Delta/W) \qquad (3)$$

If the calibration function $f(a/W, \Delta/W)$ is known, the instantaneous crack length a can be derived from eq. (3) nunmerically for every point of a load displacement record given by F and Δ. The differential equation necessary for the calculation is the following (1):

$$da = \frac{b^2/W^2 \dfrac{\partial f}{\partial(\Delta/W)} d\Delta - dF/B}{\dfrac{2b}{W} f - \dfrac{b^2}{W^2} \cdot \dfrac{\partial f}{\partial(a/W)}} \qquad (4)$$

The values of f, $\frac{\partial f}{\partial(\Delta/W)}$ and $\frac{\partial f}{\partial(\Delta/W)}$ have to be evaluated at the respective point (Δ/W, a/W) from the key curve function. For the application of this equation the a/W-dependence of load displacement behaviour has to be known. It can be determined for instance by testing subsized specimens or by calculating load displacement curves with various a/W-ratios. In order to avoid this and to make it sufficient determining only one load displacement curve for a constant a/W-ratio, an equation is required, which describes sufficient accurately how load displacement curves depend on a/W.

In (2) Ernst et al. have made a separation of variables for f(a/W, Δ/W) in eq. 3, so that:

$$f(a/W,\Delta/W) = g(a/W) \cdot H(\Delta/W) \qquad (5)$$

For 3SENB-specimens the function g(a/W) can be set equal to unity, for CT-specimens it is given by eq. (6):

$$g(a/W) = e^{-\alpha(1-a/W)} \qquad (6)$$

Replacing f(a/W,Δ/W) in eq. (3) by eq. (5) and (6) gives:

$$\frac{FW}{Bb^2} = e^{-\alpha(1-a/W)} H(\Delta/W) \qquad (7)$$

with $\alpha = 0$ for 3SENB-specimens
$\alpha = -0{,}522$ for CT-specimens

From eq. (7) a differential equation is derived from which the quantities of f, f(Δ/W) and $\partial f/\partial(a/W)$ can be evaluated, if H(Δ/W) is known. H(Δ/W) can be obtained by determining a load displacement curve for only one constant a/W-ratio experimentally or numerically. The derived differential equation for crack length determination is the following:

$$da = \frac{b}{\eta} \left(- \frac{dF}{F} + \frac{\partial H/\partial(\Delta/W)}{H} \frac{d\Delta}{W} \right) \qquad (8)$$

$$\text{with } \eta = 2 - \frac{b}{W}\alpha \qquad (9)$$

Determination of the Key Curve Function

In an earlier work (5) it was shown that a key curve function for CT-specimens can be determined calculating load displacement curves for various constant a/W-ratios within the range occurring in a specimen during a test. FE-computations were performed for a/W = 0.5 - 0.75. The resulting a/W-dependence is compared with eq. (7) in figure 1. H(Δ/W) was calculated for a/W = 0.65 meaning that the FW/Bb^2-values derived from eq. (7) have to fit the FE-calculations for a/W = 0.65. Considerable deviations of about 4% can be stated in the linear elastic region of the load displacement curves and for a/W = 0.5 in the whole Δ/W-range. It can be learnt that the a/W-ratio for which H(Δ/W) has to be determined for should be very close to the initial a/W- ratio of the test piece. In this case the maximum deviation can be limited to neglectable percentages. Therfore crack length determination can be simplified using eq. (8) instead of eq. (4) and getting along with a key curve function determined by FE-computations for only one constant a/W-ratio.

It was shown in (5), too, that the key curve function can be normalized dividing load by the lower yield strength R_{el} and displacement by the elastic strain at the lower yield strength ε_e. Therefor discontinuous yielding of the material should occur. In order to prove this in a wider strength range, two FE-computations were performed using for the second computation a stress strain curve with the double yield strength and a parallelly shifted strain hardening portion. The stress strain curves belonging to 20 MnMoNi 5 5 (1) steel are given in fig. 4. The results of the FE-computations are presented in fig. 2. A maximum deviation of about 1% was found. Applying this normalized key curve function to a range of yield strengths between 490 to 590 N/mm^2, which was done for the present work, will consequently lead to smaller deviations, which should be tolerable. Fig. 3 shows how deviations of load (due to errors) concerning the key curve functions or the experimental load measurement affects the crack length determination. It can be seen, that for a constant error of crack length Δb/W or Δa/W, the tolerable deviation of load increases with increasing a/W-ratio. This recommends to test specimens with a high a/W-ratio beeing just below the upper bound of the range from a/W = 0.5 to a/W = 0.75 which is recommended in ASTM E 813. Deviations due to the use of eq. (6) describing the a/W-dependence and due to the use of the normalized key curve function should be less than 1.5%. According to fig. 3 a maximum error of Δb/W = Δa/W = 0.0024 would result, which is 0,12 mm for a 1CT specimen.

Test Program, Materials

Chemical compositions and tensile properties of the steels investigated are given in table 1. Two types of 20 MnMoNi 55 steel have been investigated. For 20 MnMoNi 55 steels fracture mechanics tests according to ASTM 813 were performed at ambient temperature on 1CT-specimens (W = 50 mm, B = 25 mm), which were 20% side grooved. The tests were terminated at different Δ/W-values, the final crack extensions were obtained by fractography and key curve method. During one test the crack extension was monitored by DCPD-technique. Another serie of tests was done at various displacement rates from 0.01 mm/s up to 500 mm/s. Until 100 mm/s load was measured by a piezoelectric load cell and displacement using a clip gauge. At the rate of 500 mm/s the load was determined by strain gauges fixed on the specimen according to Krabiell et al. (6) and the displacement was measured by a non-contact-dicplacement measuring system working on the principle of eddy current losses. The data were stored in a two channel transient recorder with a capacity of 8 bit x 4000 words and a maximum sample rate of 20 MHz. For the Fe E 470 steel fracture mechanics tests were carried out on 20% side grooved CT-specimens (W = 80 mm, B = 35 mm) and 3SENB-specimens (W = 70 mm, B = 35 mm, S = 280 mm). J_R-curves were evaluated for the CT-type tests by multiple specimen technique and key curve method. The final crack extensions were obtained by fractography and by the key curve method for CT- and 3SENB-type tests.

RESULTS

The results are represented in figures 5 to 9. Concerning CT-specimen tests a normalized calibration function determined by FE-computation (plane strain) using the true stress strain curve of 20 MnMoNi 55 (1) steel was used to evaluate crack extensions. It was converted to the respective yield strength of the material. In fig. 4 the stress strain curves of the steels investigated are shown. The strain hardening portions are nearly parallel, the yield strengths differ. It was shown above, that in this case a normalized key curve function can be used. The comparison of crack extensions obtained by fractography (9 point average method) and derived from the calibration function is shown in fig. 5. It can be seen, that for $\Delta a > 1{,}8$ mm all data points are lying within the 10% error band. At small crack extensions the percentage of error is somewhat greater, but the maximum difference is 0,3 mm. The wider scatter of data points of the Fe E 470 steel is probably due to an irregular crack extension along the crack front, which was at both sides close to the side grooves much greater than in the middle. Therefore the error of the nine point average method will be greater and also the crack extension derived from the calibration function should be less accurate. Fig. 6 shows the J_R-curves of the Fe E 470 steel determined by multiple specimen technique and by the key curve method. J_{Ic}-values were evaluated according to ASTM E 813. For both methods the J_{Ic}-values and the tearing moduli T_{mat} derived from the slope of the regression lines agree well with one another. In fig. 7 a comparison is shown of J_R-curves determined by DCPD-technique and by the key curve method for the 20 MnMoNi 55 (1) steel. The crack length was obtained by DCPD-technique and linear interpolation between the potential at crack initiation and the final potential. A good agreement was found between both J_R-curves, J_{Ic}-values according to ASTM E 813 and T_{mat}-values.

3SENB-specimens were tested on Fe E 470 to verify the mothodology for this test piece type, too. The calibration curve was determined by FE-computations using the stress strain curve of Fe E 470 steel. As it was done for CT specimens, the tests were terminated at different Δ/W-values. In fig. 8 the crack length evaluated from the key curve function for the end of each test are plotted versus the final by fractography measured crack lengths. It can be seen that the key curve method underestimates the actual crack lengths by about 0,8 mm. All data points confirm the same tendency and therefore these results can't be explained by a scatter effect. It can be assumed, that the calibration function, determined by FE-computation doesn't represent the correct load-displacement behaviour. Because of the fact that all crack extensions are underestimated by about the same amount, the key curve function should be stiffer. One possible reason for this is, that the FE-compuation didn't account for friction and plastic deformation between rollers and specimen surface. Taking these effects into consideration higher load values would be obtained, whereas the displacement measurement would not be affected, because it was measured on the specimen. Further efforts have to be made on taking friction effects and plastic deformation into account at the FE-computation, or on improvements of the three point bend fixture to minimize friction effects.

Because the method could be successfully applied to CT-specimens, the key curve method was used to determine J_R-curves at high displacement rates. Tests were performed between ram displacement rates from 0.01 up to 500 mm/s on 1CT-specimens. The results are shown in fig. 9. A slight increase of crack resistance behaviour was found with increasing strain rate.

CONCLUSIONS

The key curve method can be applied successfully to determining J_R-curves with CT-specimens using a calibration curve obtained by FE-computations. The method can be simplified by using a normalized key curve function and an equation describing approximatly the a/W-dependence of the normalized load, if the following requirements are met:

- the yield strength and the Lüders-strain of the material should be not too different from that the calibration curve was determined with
- the a/W-value of the calibration curve should approximately

correspond to the initial crack length of the specimen

The results of crack length determination are in good agreement with by fractography obtained crack lengths. The determined J_R-curves and also J_{Ic}- and T_{mat}-values are nearly identical compared with by DC-potential drop and multiple specimen technique.

The key-curve method can be used to determine J_R-curves at high displacement rates, if an accurate load displacement curve can be obtained. A slightly increasing crack resistance in terms of J_R- curves was found for a 20 MnMoNi 55 steel with higher displacement rates.

Tests on 3SENB-specimens led to considerable deviations of key curve results and measured crack lengths. This is probably due to friction and plastic deformation between roller pins of the specimen fixture and the specimen surface, which was not taken into account at the FE-computation for the calibration curve. Further improvements have to be made concerning the FE-computations or the specimen fixture.

SYMBOLS USED

a	= crack length
b	= specimen ligament size
B	= specimen thickness
F	= load
$f(a/W,\Delta/W)$	= key curve function
$g(a/W)$	= function describing a/W-dependence of $f(a/W,\Delta/W)$
$H(\Delta/W)$	= function describing Δ/W-dependence of $f(a/W,\Delta/W)$
J	= J-Integral
J_{Ic}	= J-Integral for crack initiation according to ASTM E 813
T_{mat}	= tearing moduls
W	= specimen width
d	= factor, describing a/W-dependence
Δ	= load line displacement
η	= $2 - \alpha\, a/W$

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Steel	C	Si	Mn	P	S	Al	Cr	Ni	Mo	V	Zr
20 Mn Mo Ni 55 (1)	0.20	0.24	1.40	0.007	0.003	0.029	0.16	0.74	0.48	—	—
20 Mn Mo Ni 55 (2)	0.20	0.24	1.38	0.011	0.005	0.068	0.06	0.52	0.53	—	—
Fe E 470	0.15	0.33	1.20	0.020	0.011	0.024	0.03	—	0.31	0.01	0.044

Steel	Yield Stress $[Nmm^{-2}]$	Tensile Strength $[Nmm^{-2}]$	Elongation [%]	Reduction of Area [%]
20 Mn Mo Ni 55 (1)	585	695	19.2	68.4
20 Mn Mo Ni 55 (2)	540	675	24.0	67.0
Fe E 470	495	605	18.3	70.0

Table 1. Chemical compositions and tensile properties of the steels investigated

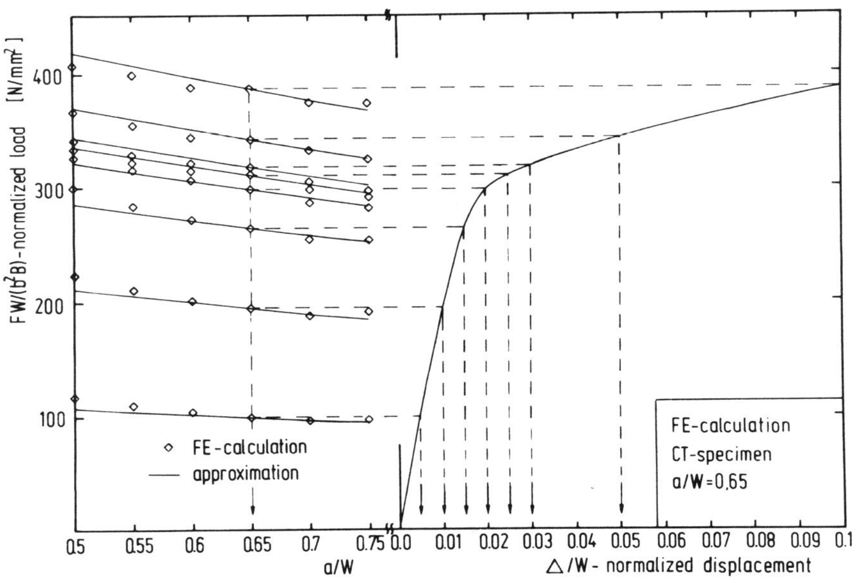

Figure 1. Comparison of FE-calculations and the approximation describing a/W-dependence according to Ernst et al. (2)

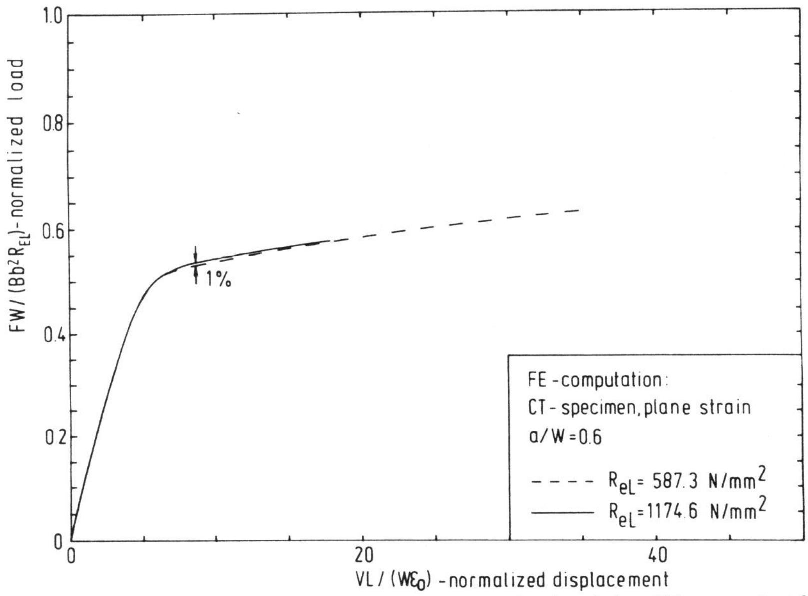

Figure 2. Normalized calibration curves derived by FE-computation from stress strain curves with different yield strengths

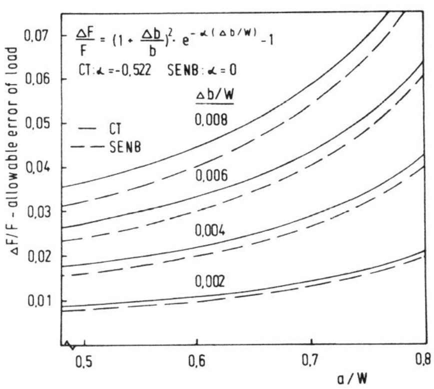

Figure 3. Estimation of errors

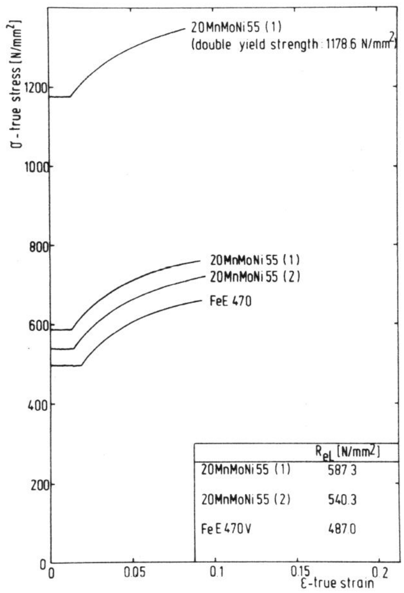

Figure 4. Stress strain curves of the steels investigated

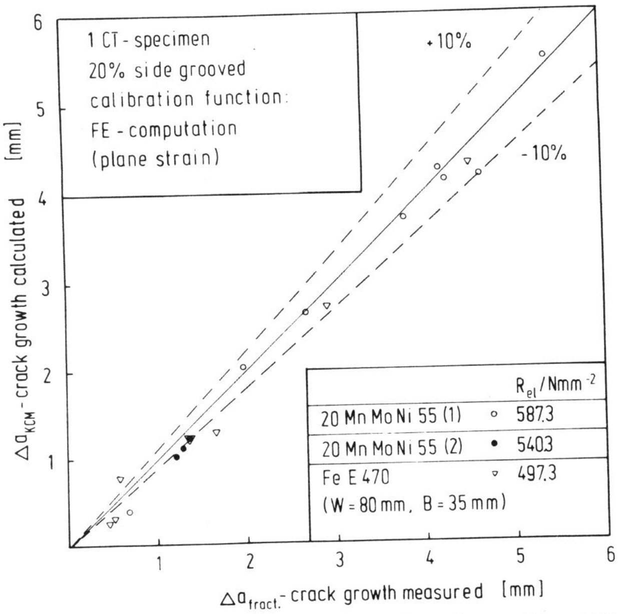

Figure 5. Calculated crack extensions vs. crack extensions obtained by fractography

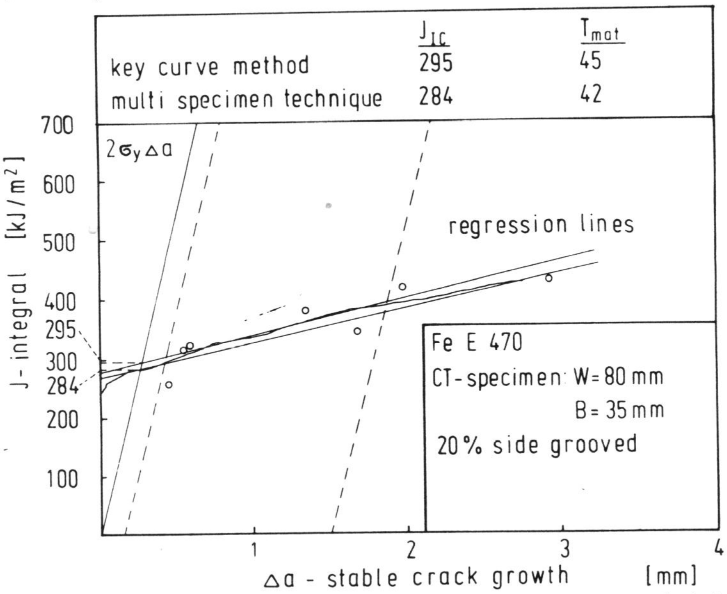

Figure 6. Comparison of J_R-curves determined by multiple specimen technique and key curve method

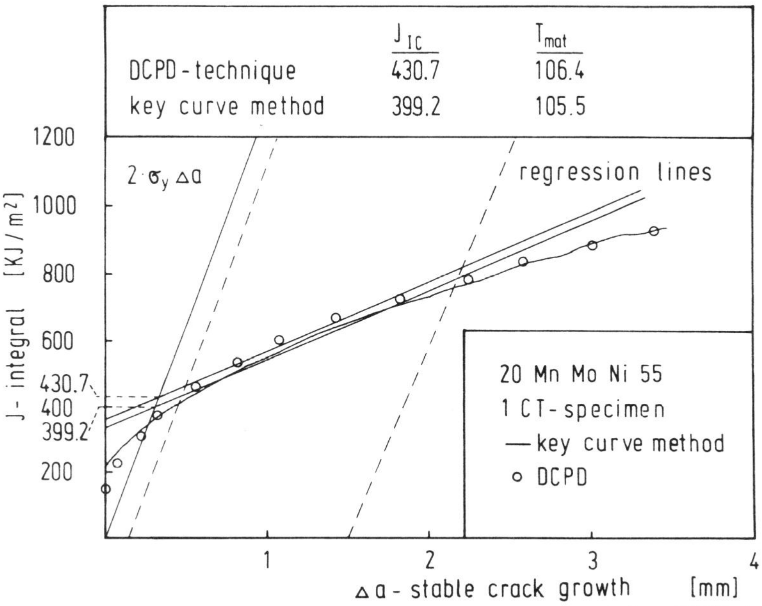

Figure 7. Comparison of J_R-curves determined by DCPD-technique and key curve method

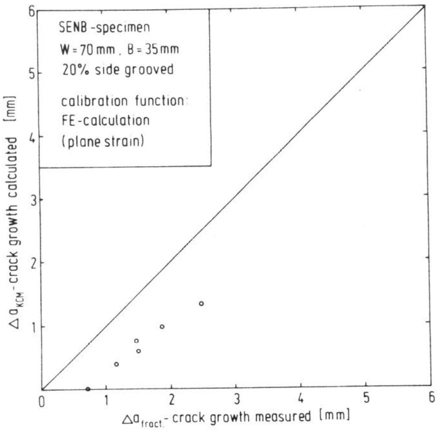

Figure 8. Calculated vs. measured crack extensions

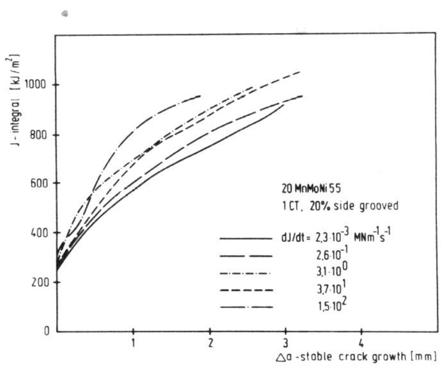

Figure 9. J_R-curves of steel at various loading rates