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THE EVALUATION OF THE RESISTANCE AGAINST DUCTILE CRACK EXTENSION

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INTRODUCTION

Single edge notched specimens were torn to complete fracture in a ductile way by excentrical pin loading under constant displacement speed; 3-points bend notched specimens were fractured in the ductile region by impact loading. The load P/deflection f-diagram was recorded and the cracklength a simultaneously filmed.

The resistance R against crack extension was evaluated, using an energy balance analysis, which appears applicable in the elastic, elastic-plastic and fully plastic situation. The importance of a distinction between energy dissipated for crack extension and energy dissipated in an accompanying but alternative way as determined by the test and specimen conditions for indicating the actual crack resistance of the material is argued.

The influences of initial crack tip radius, finiteness of ligament length (w-a) and height h of the specimens are briefly discussed to account for the observed anomalous R-curve behaviour.

This investigation was performed with special reference to the ductile shear fracture as can unstably occur in steel gas pipes if work is performed by the gas on the fracturing vessel wall and aimed at evaluation of the resistance against large scale crack extension as far as determined by the material properties. For the relevant case of sufficiently low crack velocity the displacement speed controlled tests allow to determine R after "unstability" in a quasi static way.

If work A is done on a precracked specimen, as in a "constant displacement speed" controlled experiment, instability of the crack implies that the rate of work can decrease for its further extension. For a sufficiently slow crack velocity $\dot{a}$ the load P can quasi-statically adjust itself to the compliance change and thus decreases. As a consequence the generation of kinetic energy V is then negligible. The energy absorbed during fracture (the fracture energy) contains (recoverable) elastic energy U and dissipated energy W. The latter can for a part W_a be connected to the effective surface energy, mostly consumed to propagate the plastic zone size at the crack tip. However a dissipation of energy W_d can also occur by processes not to be linked directly with the actual crack extension, but occurring where the stress is raised above yield by other influences than the crack tip field (below general yield this is revealed by non-coherent plastic regions possibly involving compressed ones). For this situation the l e f m approach including plastic zone corrections will not be amenable. The total resistance against fracture:

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$$R = \frac{dW}{da} = \frac{dW_a}{da} + \frac{dW_d}{da} = R_a + R_d \tag{1}$$

then contains besides the crack resistance R_a or the effective surface energy (this being the material property of primary interest), also a term R_d.

Obviously, R can only be a constant, if $R_d = 0$ or constant, conditioning validness of $J_{Ic} = R_a$ at first physical crack growth, when J_{Ic} is evaluated from an integration of the load/deflection diagram.

Assumedly R_a will be dependent on $\dot{a}$ and possibly on a, while as elaborated below there will be an influence of the finite specimen dimensions on R_a. This is contrary to current (l e f m) material concepts, which claim that a suitable geometrical correction factor in the corresponding mechanical fracture mechanics concepts, allows for a critical fracture mechanics material value not dependent on dimensions or geometry. However, the anticipation that a R_a-value only dependent on $\dot{a}$ can be indicated, characterizing the material for suitably chosen large dimensions with absence of free surface influences, can be considered an instigation to this investigation.

THEORETICAL

In the following an evaluation of fracture resistance during large scale extension - thus not restricted to the quasi static crack growth after first physical crack propagation up to instability, but also for the state thereafter - is suggested from an energy balance analysis.

For the deflection of a loaded specimen one can write:

$$f = f_e + f_p \;;\; f = f(a,P) \tag{2}$$

f_e is the reversible, f_p is the irreversible part of f.

$$CP = C_eP + C_pP \;;\; C_e = C_e(a) \;;\; C_p = C_p(a,P) \tag{3}$$

$$\Delta f = \Delta f_e + \Delta f_p = C_e\Delta P + C_p\Delta P + P\frac{dC_e}{da}\Delta a + P\left(\frac{\partial C_p}{\partial a}\right)_P \Delta a + P\left(\frac{\partial C_p}{\partial P}\right)_a \Delta P \tag{4}$$

C = compliance; index e refers to elastic, index p to plastic.

The energy balance will read:

$$Pdf = \bar{d}A = \bar{d}Q + dW + dU + dV = TdS + Rda + dU + dV \tag{5}$$

T = absolute temperature, S = entropy.

For the case of interest here, dV = 0 as elaborated above. It will moreover be understood that TdS is incorporated in R, or rather with the right proportion in R_a and R_d.

$$Pdf = \left\{PC_e + PC_p + P^2\left(\frac{\partial C_p}{\partial P}\right)_a\right\}\frac{dP}{da}\,da + \left\{P^2\frac{dC_e}{da} + P^2\left(\frac{\partial C_p}{\partial a}\right)_P\right\}da \tag{6}$$

and also for unit thickness:

$$Pdf = dW + dU = Rda + d\left(\frac{C_eP^2}{2}\right) = Rda + \left\{C_eP\frac{dP}{da} + \frac{P^2}{2}\frac{dC_e}{da}\right\}da \tag{7}$$

$$R = \frac{P^2}{2}\frac{dC_e}{da} + \left\{PC_p + P^2\left(\frac{\partial C_p}{\partial P}\right)_a\right\}\frac{dP}{da} + P^2\left(\frac{\partial C_p}{\partial a}\right)_P \tag{8}$$

Note I:

1° $$\frac{dU}{da} = C_eP\frac{dP}{da} + \frac{P^2}{2}\frac{dC_e}{da} \tag{9}$$

2° If P = constant, $$R = \frac{P^2}{2}\frac{dC_e}{da} + P\left(\frac{\partial C_p}{\partial a}\right)_P \tag{10}$$

3° If l e f m applies, i.e.

$$C_p = 0 \;;\; C = C_e \text{ and } R_e = \frac{P^2}{2}\frac{dC}{da} \tag{11}$$

4° $$R = R_e + R_p \tag{12}$$

5° $$\bar{d}A = Pdf = dU + R_e da + R_p da \tag{13}$$

R has only to be interpreted as R_a, when $W_d = 0$ of $dW_d/da = 0$. Recordings of a load/displacement curve for a specimen of interest e.g. an excentrical pin loaded single edge notched (e p l s e n) specimen, while unloading and reloading again for certain cracklengths obtained by increasing crack extension, allow to estimate $C_e = C_e(a)$. This can be compared with a numerically evaluated $C_e = C_e(a)$ using finite element method technique. If the agreement is satisfactorily verified the latter can substitute the former (cf. however Results). R can now be correspondingly determined.

Note II:

If no kinetic energy is generated, i.e. the load adjusts itself to the compliance at each moment:

$$\dot{A} = P\dot{f} = R + \frac{dU}{da}\dot{a} \tag{14}$$

For dU/da << R this implies:

$$\dot{a} = \frac{\dot{A}}{R_a + R_d} \tag{15}$$

EXPERIMENTAL

Single edge machine notched specimens were torn to complete fracture by excentrical pin tensile loading, sometimes wedge loading, using a 250 tons MTS-closed loop system equipment in a displacement speed controlled way. The crack proceeded in a ductile way at velocities, which were so small (10 cm/sec) that at each moment the load could adjust itself to the increasing compliance in a quasi static way.

Three line pipe steels, with properties as indicated in Table 1, were tested in 3-fold, using e p l s e n-specimens at displacement speeds of 9 and 25 mm/sec; one material was moreover tested in 3-fold using wedge loaded single edge notched (w l s e n) specimens at the same displacement speeds. The load-deflection diagram was recorded; the extending crack was filmed.

As the w l s e n-specimen showed a severe liability to buckling, all specimens were adapted with stiffener beams, bolted at both sides of the specimen and meeting as a hinge just outside the specimen opposite the advancing crack tip. The applied specimen dimensions are shown in Figure 1. Initial machined notches of mostly 60, also 100 and 140 mm were introduced. For each material one extra specimen was used for finding the elastic compliance as a function of cracklength. This proceeded by unloading after some crack extension, then loading again, and repeating this after some additional crack extensions, several times, till the ligament was completely torn.

A small hysteresis was observed by unloading and reloading, slightly increasing with increasing cracklength.

This did not interfere with a sufficiently accurate estimate of the elastic compliance C_e as a function of a. The dependence of the elastic compliance on cracklength both with and without stiffeners to the specimen as observed was compared with a numerical evaluation using the finite element method, applying a substructuring technique. The relevant elements division is illustrated in Figure 2.

This allows in principle to interpret the cracklength as observed at the surface in a for the compliance effective one, in this way taking into account the protruding of the crack tip in the core of the plate specimen.

Single edge machine notched specimen (with a height of 100 mm and initial notch length of 15 mm; cf. Figure 1c) were dynamically tested in 3-points bending by a falling weight of 280 kg mass from a height of 2.60 m. The striker was straingauge instrumented, allowing to record load in time. The crack propagation was filmed (using a Dynafax camera).

RESULTS

For the e p l s e n specimens R/a-curves as inferred from the load/deflection diagram and corresponding $\dot{a}$/a and R/$\dot{a}$ curves are shown in Figures 3a, 3b, 3c respectively. The low $\dot{a}$ and its small variations in these experiments obviously did not influence R. After a preambulary phase the R-curves appear rather independent of a_0, the initial notch length. A recording for determining the elastic compliance dependence on a is shown in Figure 4a. The deduced C_e(a)-curve (cf. Figure 4b) did not quite agree with the numerically evaluated one using the finite element method for the stiffened specimens. The dissipated energy W to accomplish

a certain crack extension was determined from the load/deflection diagram as well, duly taking into account the elastic energy correction. Cf. Figure 5. The W/a curve was polynomium fitted as:

$$W = W_0 + W_1(a-a_0) + W_2(a-a_0)^2 + W_3(a-a_0)^3 + W_4(a-a_0)^4 \qquad (16)$$

with a_0 = initial notch length.

The R-value at $a = a_R$ for which $d^3W/da^3 = 0$, was taken as R-reference for the material (cf. Discussion). For these and other data of the investigated line pipe steels cf. Table 1. Results of R/a, $\dot{a}$/a and R/$\dot{a}$-curves for the striker instrumented drop weight tear tests are given in Figure 6.

DISCUSSION

The start of physical crack extension as observed at the surface will lag behind to that actual according in the core of the material thickness. If the protruding of the crack tip still increases, the real crack extension will be underestimated by a surface crack observation, implying an overestimate of R. Recordings of crack extension by an electrical potential method can overcome this difficulty, but due to influences of the plastic development on the electrical resistance the physical crack extension effect tends to get blurred. If the initial notch is machined as in most of these experiments one might expect that the finite tip radius will cause first physical crack extension to occur for a R_a substantially larger than J_{Ic}. The development of a possible sharper crack tip after some crack extension will have a corresponding lowering effect on R. However, experiments on fatigue cracked specimens showed only a minor decreasing effect for the initial R-values as compared to those occurring for the machine notched specimens.

A dissipation of energy W_d not connected with the crack extension will be more pronounced in the first phase of the experiment as well, when dealing with a high load. It is due to bending of the separated parts, deformation of the bolt holes etc.

When general yield occurs, possibly already at the onset of real crack growth, less plastic work will be dissipated pro cm crack extension the more the ligament decreases, thus decreasing R with increasing a. The deformation has to comply with the displacements as enforced by the stiffeners, implying at each moment a displacement, where these are localized, linearly approaching zero with the distance to the hinge. The resulting constraint on plastic development will progressively decrease R the more the crack tip has penetrated through the ligament.

The above mentioned effects all contribute to the anomalous R-curve behaviour showing instead of the initial increase, merging into a rather constant level, a decrease with an inflexion point, i.e. with a $dR/da < 0$ showing a maximum, for which thus $d^3W/da^3 = 0$ (and $d^4W/da^4 < 0$).

If the disturbing influence of the initial phase at real crack extension implying an overestimate of R, overlaps the region of influence of the terminal phase for which R tends to get underestimated, an anticipated constant R-level will be obscured, but still introduces this inflexion point in the R/a-curve. This was used to approximate the undisturbed R-level. The impact test results obtained until now suggested that a rather constant R-level might become realized in the advanced phase of crack extension, cf. Figure 6a. The small differences between the line pipe materials could be revealed by separation of the R/a-curves for the e p l s e n-specimens in a significant way. Cf. Figure 7.

The influence of dimensions on estimated R-values is yet not quite clear. Besides the finite ligament width also the height of the specimen might exercise constraining influences on the plastic flow development connected with the crack extension.

Instead of aiming at a plastic flow development as free as possible by increase of dimensions, one could also try to achieve a high constraint. Therefore sidegrooving along the anticipated crack path was introduced. These experiments are still in progress. While in general can be referred to [1], as recently appeared related work can be mentioned [2], [3] and [4].

CONCLUSION

Contrary to J_{Ic}-evaluations, requiring the detection of the onset of first physical crack growth and rejecting (large scale) crack extension, the R/a-determination can proceed in a quasi static way for large scale ductile crack extension with velocities up to 1-100 m/sec. The only restriction appears a possible dissipation of energy not to be identified with that required for crack extension. (This will unfavourably interfere with all other fracture mechanics determinations). Estimates of G_{Ic} or J_{Ic} from small specimens, using the R/a-determination appear quite feasible, (extrapolation from small crack extensions to zero offering) the J_{Ic}-values, showing only slight discrepancies with R. As the irreversibility of the deflection is incorporated in the analysis for determining R there is no need to discuss "pseudo potential energy".

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Table 1

line pipe steels cast	yield strength [MN/m²]	ultimate tensile strength [MN/m²]	area reduction in tensile test [%]	2/3 Charpy V at 0°C [MN/m]	R [MN/m]	a_R [mm]
4338	427	524	69.0	1.09	2.5	144
7898	460	564	72.0	1.71	3.5	130
8380	420	502	76.5	2.12	4.5	125

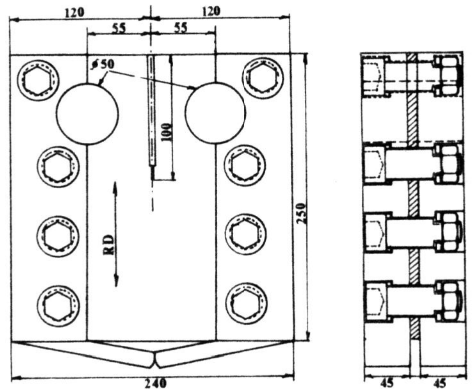

Figure 1a Eplsen - Specimen, Provided with Stiffeners Hinge

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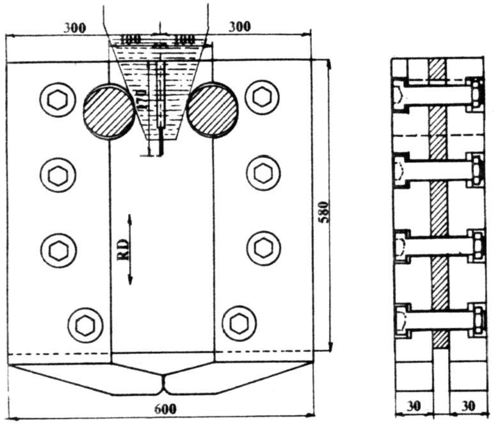

Figure 1b Wlsen - Specimen, Provided with Stiffeners Hinge

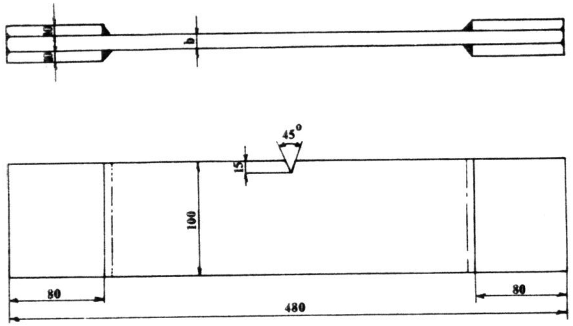

Figure 1c Three-Points Bend Sen-Specimen for Impact Testing

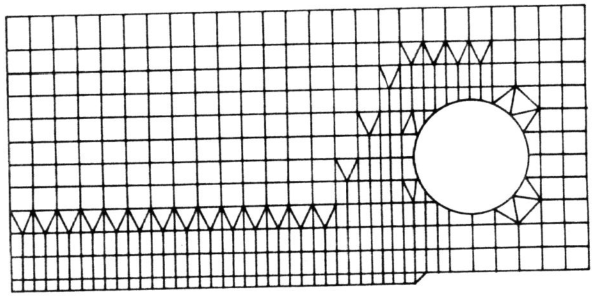

Figure 2 Elements Distribution for Numerical Evaluation of Dependence of Elastic Compliance on Cracklength, Using the Finite Element Method with a Substructuring Technique

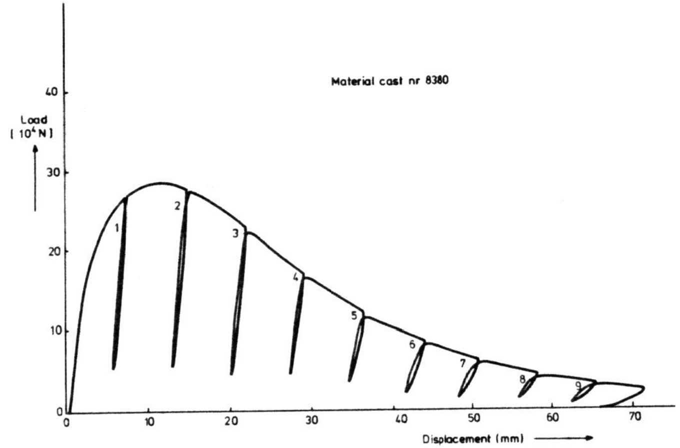

Figure 3a Recordings of Load/Deflection Diagram for Eplsen-Specimen at Repeated Unloading and Loading After Subsequent Crack Extension for Evaluation of Dependence of Elastic Compliance on Cracklength

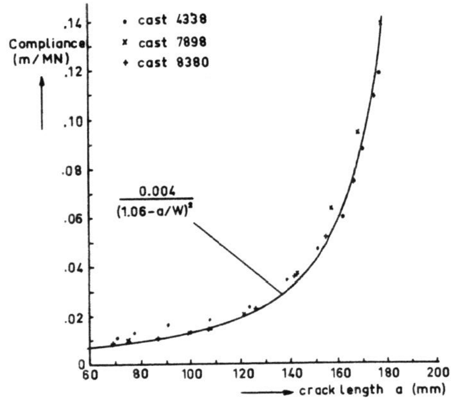

Figure 3b Elastic Compliance Dependence on Cracklength According to Recordings Shown in Figure 3a

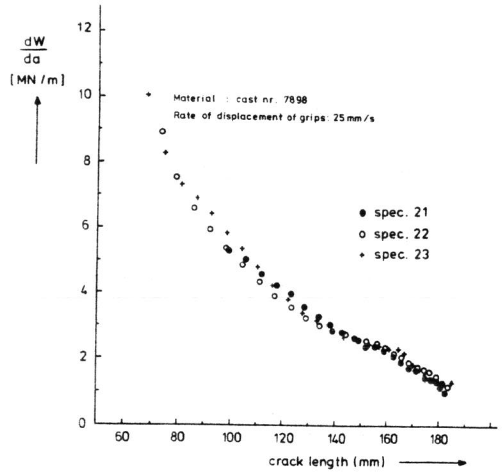

Figure 4a Fracture Resistance Dependence on Cracklength in Tested Eplsen-Specimens at Displacement Speed of 25 mm/sec

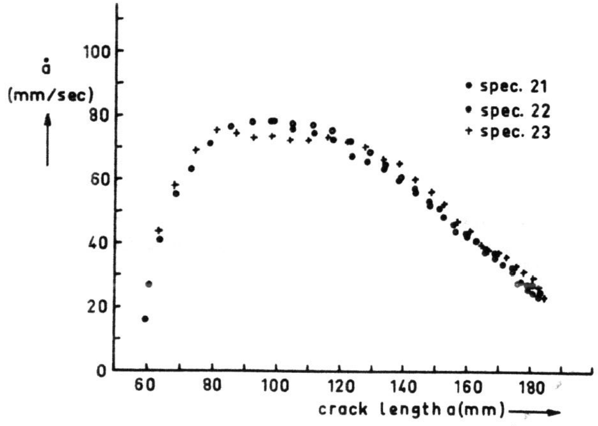

Figure 4b Fracture Velocity Dependence on Cracklength in Tested Eplsen-Specimens at Displacement Speed of 25 mm/sec

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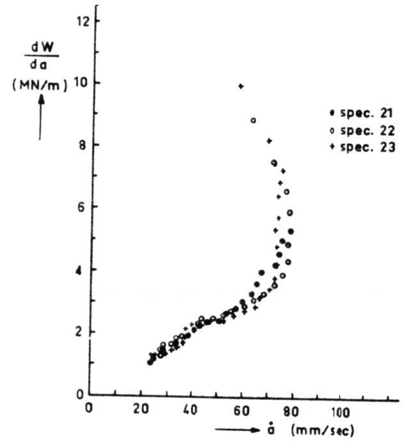

Figure 4c Fracture Resistance Dependence on Crack Velocity in Tested Eplsen-Specimens at Displacement Speed of 25 mm/sec

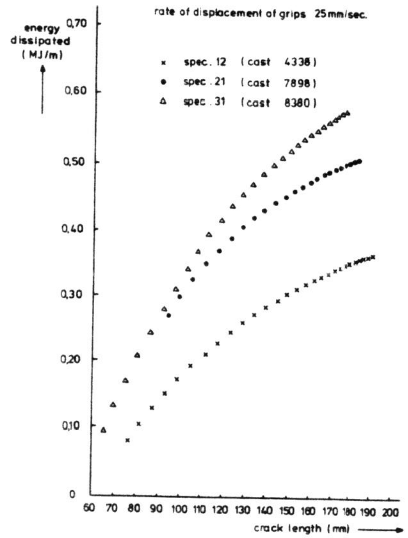

Figure 5 Energy Absorbed as a Function of Cracklength for Extending Crack in Eplsen-Specimens at Displacement Speed of 25 mm/sec

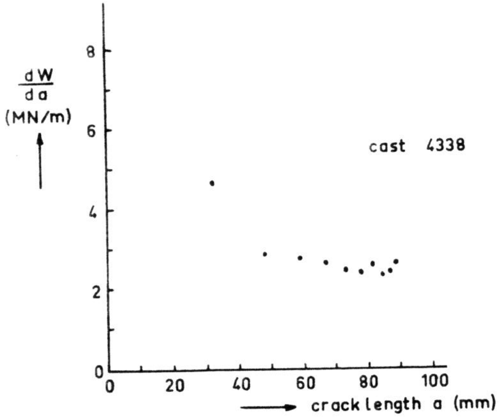

Figure 6a Fracture Resistance Dependence on Cracklength in Impact Tested Three-Points Bend Sen-Specimen

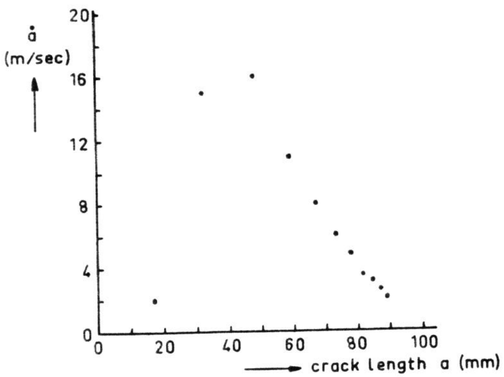

Figure 6b Fracture Velocity Dependence on Cracklength in Impact Tested Three-Points Bend Sen-Specimen

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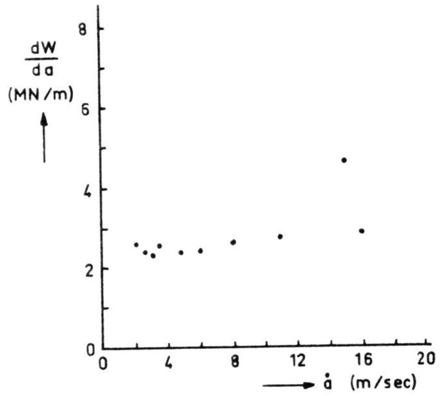

Figure 6c Fracture Resistance Dependence on Crackspeed in Impact Tested Three-Points Bend Sen-Specimen

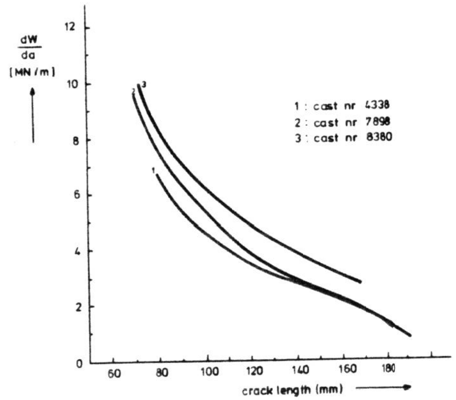

Figure 7 Average R/a Curves for Three Line Pipe Steels, According to Testing of Eplsen Specimens