CRACK GROWTH ANALYSIS IN CLADDED REACTOR COMPONENTS BY MEANS OF FRACTURE MECHANICS

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SUMMARY

The safety of components against untolerable crack growth can be predicted by means of fracture mechanics. In order to show the accuracy of these predictions, failures of real structures have to be analyzed. Sometimes the applicability of fracture mechanics theory is questioned because of discrepancies between theoretical and experimental results. The criticism of the theory, however, is not justified unless the correct application of the theory is examined carefully. Fracture mechanics equations are rather simple, but a lot of parameters and influences are more difficult to assess.

These parameters are:

— The crack shape is very important for the stress intensity factor. For the evaluation of arbitrary natural crack shapes, however, only a few idealized geometries are available. Also the behavior of a crack is affected by adjacent defects.
— Stress concentrations due to changes in thickness or local loads have to be considered.
— Residual stresses must not be neglected since their effect on brittle fracture is the same as that of thermal stresses.
— The material data for fracture mechanics are to be found by examining samples undergoing the same load conditions (plain stress, plain strain) as the components.
— Especially for the crack growth, the influence of the mean value of oscillating stresses or even of compressive stress amplitudes is important.

In this report, the growth of a flaw situated under the cladding of a simple structure similar to a reactor component wall, is analyzed. First the behavior of the crack is limited by a very conservative solution and by a most favourable estimation. Both these curves (crack size versus cycles) are identical at the beginning whereas they diverge extremely at an increasing number of cycles. Then the measured values between these extremes are met with more detailed, realistic assumptions.

For safety evaluations, conservative solutions have to be used whereas a failure analysis has to show both the extremes between which the real defect behaviour is expected.

On the basis of the measured crack growth in the specimen and on the basis of the particular geometry and assumed loading history of a steam generator wall, it is possible to estimate the growth of an undercladding crack.

Fracture mechanics enables the safety of components to be predicted. Such predictions have to be confirmed by a failure analysis being subsequently explained on real components. Fracture mechanics assessement of such failures often cause the theory to be inaccurate or even unusable because, for instance, the actual and theoretical bursting pressure of a vessel exhibit considerable discrepancies. But this conclusion is not correct before a close check has been made as to whether the theory has been applied properly.

The fracture mechanics equations look rather simple but the values to be inserted and the marginal conditions to be allowed for are often less lear than they appear to be at first sight. Here are a few examples:

- The crack geometry influences the stress intensity. But while the crack geometries are arbitrary and natural, equations have been established only for idealized geometries. Neighbouring flaws in clusters will influence one another.

- Stress concentrations due to changes in cross section or local concentration of stress should be duly taken into account.

- Residual stresses have the same effect on brittle failure behaviour as thermal stresses have.

- The fracture mechanics material parameters shall be obtained from specimens that are subject to the same load condition (plane strain, plane stress) as that existing in the component.

- As regards crack growth, the effect of mean stress (crack growth due to the compression amplitude) has to be considered in addition.

The following describes the method of fixing an upper and lower limit of crack growth in a simple component. Following this, an attempt is made to define as closely as possible the real behaviour of the flaw on the basis of more accurate estimates.

<u>Geometry:</u> (Fig. 3) 36 mm width, 6 mm of which have a cladding overlay, 6 mm thick
Initial crack depth a_o = 2.5 mm (counting from the fusion line down into the base metal)

<u>Fully reversed load:</u> Upper load = + 102 000 N
Lower load = - 86 000 N

<u>Behaviour of material:</u> (Fig. 1) Base material 22NiMoCr37. The crack growth parameters "Co" and "n" are determined by measurements [1]. For the range of ΔK from 2.10^3 to 5.10^3, as occurs in our case, "n" is taken to be 3.1 and "Co" to be $4.5 \cdot 10^{-14}$.

<u>Equations for estimating the crack growth:</u>

$$\frac{da}{dN} = Co\,\Delta K^n \qquad (1)$$

$$\Delta K = \Delta\sigma \cdot \sqrt{\pi \cdot a} \cdot f(a/b) \qquad (2)$$

The flaw is located neither exactly at the center nor exactly at the edge. Since however it is near the edge the form factor f(a/b) for unfavourable edge cracks [2] is chosen, "b" (width of base material) being assumed to be 30 mm.

$$f(\tfrac{a}{b}) = 1.12 - 0.23(\tfrac{a}{b}) + 10.55(\tfrac{a}{b})^2 - 21.48(\tfrac{a}{b})^3 + 30.38(\tfrac{a}{b})^4 \qquad (3)$$

Substituting equations (2) and (3) in (1), numerical intergration of the differential equation

$$\int_0^N dN = \frac{1}{C_o} \int_{a_o}^{a} \frac{da}{[\Delta K(a)]^n}$$

results in "N" being a function of "a", that is to say, the crack size "a" depends on the number of load reversals "N" (Fig. 2).

The values b, a_o, f(a/b), Co, n required for the equation are known. Still missing is the stress fluctuation $\Delta\sigma$, to which the crack growth is due. The following assumptions may be possible:

Upper stress = + 102 000 N/6 36 mm^2 = + 470 N/mm^2
Lower stress = - 86 000 N/6 36 mm^2 = - 400 N/mm^2

<u>Minimum estimated value σ^u:</u> Under compression, the crack is closed so that no stress intensity exists and no crack growth results. Inserting

$\Delta\sigma = \sigma^o$ = 470 N/mm^2 then produces the curve IV shown in Fig. 2.

Upper estimated value σ^u: For safety reasons, $\Delta\sigma = \sigma^o - \sigma^u$ =870 N/mm^2 may be used, which leads to curve II (Fig. 2).

The undercladding cracks are evaluated by even stricter standards: according to the guidelines of the ASME code, the cladding is not regarded as load-bearing. Then,

σ^o = 102 000 N/6 30 mm^2 = 565 N/mm^2

σ^u = - 86 000 N/6 30 mm^2 = -475 N/mm^2

The resulting $\Delta\sigma$ = 1040 N/mm^2 leads to curve I (Fig. 2).

The actual crack growth lies between these extreme estimates and can be determined also theoretically on the basis of appropriate assumptions.

Closer assumptions of the stress are shown in Fig. 3. The nominal stress existing throughout the cross section at maximum tension is σ_n = 470 N/mm^2. Since the yield point in the cladding is less than σ_n, the base metal must, for reasons of equilibrium, take an additional constant stress $\Delta\sigma$ and a bending moment σ_b. For the stress amplitudes in the tensile and compression range the stress intensity is calculated by [2].

$$\Delta K = \int_0^a \frac{2 \cdot \sqrt{a} \cdot \Delta\sigma(y)}{\sqrt{\pi(a^2 - y^2)}} \, dy \cdot f\left(\frac{a}{b}\right)$$

Under tension the crack opens, the lines of force are diverted, resulting in a stress intensity at the crack tip. The initial compression causes the crack to close, the compressive stresses are transmitted, no stress intensity occurs at the crack tip. If there is a reversed tension-compression stress, the crack tip and, in this case, also the cladding undergo plastic deformation, leaving the crack open after the stress has been relieved. It is only on further increasing compression that the gap is closed. This is then followed by stress intensity also under compressive conditions which, as the compressive stress rises further and the crack is closed, does not continue to rise. Half the compression stress amplitude should be a realistic value for the calculation of the crack growth curve III (Fig. 2) [3].

The increase of the crack size after 600 load cycles under the conventional and the unduly favourable assumed conditions results in a difference by a factor of 40. In evaluating the flaw, at least the two extreme limits - least favourable and most favourable results - should be considered. In evaluating the safety of components the conventional solution should be used.

References

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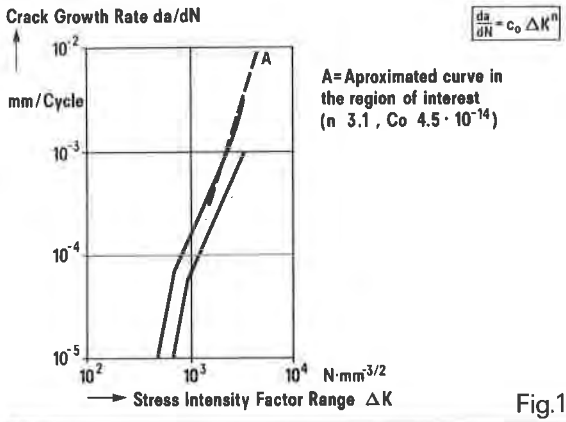

Fig.1

Scatter Band of Crack Growth Rate (22 Ni Mo Cr 37)

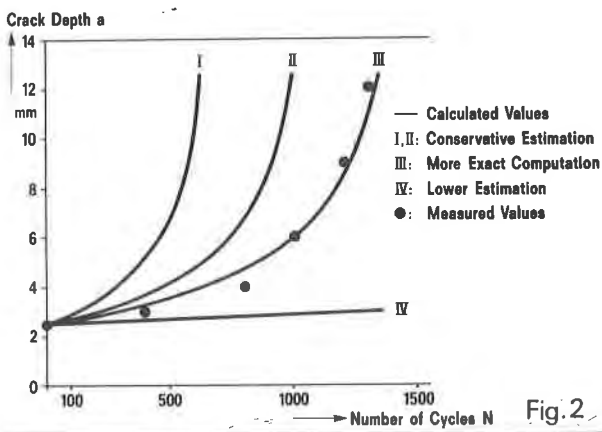

Fig. 2

Crack Depth as a Function of the Number of Cycles

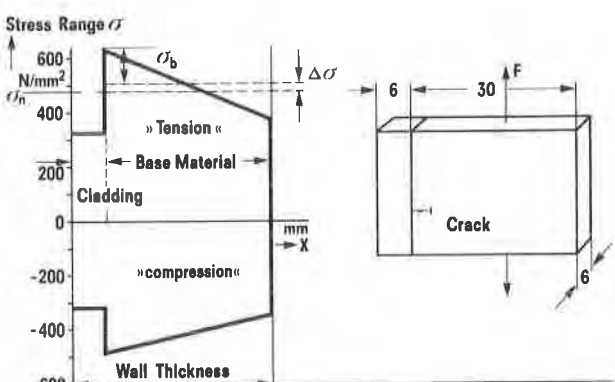

Fig. 3

Stress Range ∅ versus the Wall Thickness