FRACTURE BEHAVIOUR INVESTIGATIONS OF 10 Cr Mo Ni Nb 910 STEEL PIPES

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ABSTRACT

Experimental investigations were made in order to test the fracture behaviour of the primary coolant pipe system of the sodium cooled KNK test reactor. The experiments were conducted with through-wall flawed specimens of the original pipes used in the loop of the reactor. The theoretical investigations of the fracture mechanics predict, that even at room temperatures unstable fracturing can be excluded, so that it definitely can not occur at operating conditions. The critical crack sizes are so large, that system failures will manifest themselves by leaking prior to fracture. For the double pipe section used in the loop between valves and reactor vessel it can, therefore, be concluded that the outer pipe can not be damaged by the loss of integrity of the inner pipe. Since it is safe to say that no sudden rupture can occur.

Further investigations are planned in order to study the subcritical crack growth behaviour on more complex shapes.

1. INTRODUCTION

The investigations were planned in order to demonstrate that unstable fracture is improbable in the primary coolant pipe system of the sodium cooled KNK test reactor.

Because of the high toughness of the 10 Cr Mo Ni Nb 910 steel and since the dependence of fracture toughness on the material thickness is well known, the experiments were carried out, using pipe specimens of the original design size of the loop. Following the concept of full-scale testing, as proposed by DUFFY et al. /¯1_7 uncertainties in the fracture toughness measurements by stress or strain conditions could be avoided. Three pipes with artificial, axial through-wall flaws of different length were tested at room temperatures, i.e. in the NDT-range of the material. They were end capped and pressurized hydraulically. The through-wall flaws ended in notch root radii of 0.001 in., which were produced by a wedge. The flaws were sealed with patches, and instrumented with strain gages near the notch tip. The experimental results are discussed in very much the same way as it has been done by EIBNER et al. [2]. A summary of the experimental and calculated results is given in Table 1. In order to demonstrate the ductile behaviour, photographs of the fractured pipes are shown in Figures 5 and 6.

2. NOTATION

K_c - critical stress intensity factor

R - radius of the pipe

D - diameter of the pipe

t - wall thickness

c - half crack length

c_e - effective half crack length; Appendix of Ref. [2]

σ_h - hoop stress at failure

σ_y - yield stress

σ_u - ultimate stress

$\sigma_c = \frac{\sigma_y + \sigma_u}{2.4}$; failure stress for unflawed pipe

$\sigma^* = 1.04\,\sigma_y + 10.0$ ksi

$\Theta = \frac{\pi}{2} \frac{\sigma_h}{\sigma_c}$

M - stress magnification factor

ν - Poisson's ratio

$$\varkappa = \begin{cases} \frac{3-\nu}{1+\nu} & \text{plaine stress} \\ 3 - 4\nu & \text{plaine strain} \end{cases}$$

$\left.\begin{matrix} A \\ K \end{matrix}\right\}$ - empirical constants; Ref. [8]

3. THROUGH-WALL CRACK FORMULATIONS

The following formulations, taken from the review paper of EIBNER et al. [2] were used to determinate the critical axial crack lengths for cylindrical shells. The critical stress intensity factor as originally developed by DUFFY et al. [3], reads in the modifications of FOLIAS [4], ERDOGAN and KIBLER [5] as follows

$$K_c^2 = \frac{\pi c \sigma_h^2}{\cos \Theta} \cdot M^2 \cdot \left(\frac{4 - \varkappa}{2}\right) \qquad (1)$$

With $M^2 = (1 + 1.61 \frac{c^2}{Rt})$ for the stress magnification factor one obtains the DUFFY-formulation

$$K_c^2 = \frac{\pi c \sigma_h^2}{\cos\Theta} \cdot \left(1 + 1.61 \frac{c^2}{Rt}\right)\left(\frac{4-\varkappa}{2}\right) \tag{2}$$

The comparison of the M-factors is given in Figure 1. Due to the high toughness of the material tested, the λ values are rather large, so that for values greater than 8 the following linear approximation was used

$$M = 0.8 + 0.467\,\lambda \tag{3}$$

From experimental considerations REYNOLDS [6] suggested a modification of Eq. (1) in which the term $\frac{4-\varkappa}{2}$ has been neglected:

$$K_c^2 = \frac{\pi c \sigma_h^2}{\cos\Theta} \left(1 + 0.4 \frac{c^2}{Rt}\right) \tag{4}$$

HAHN et al. [7] proposed two formulations valid for different ranges of toughness and crack lengths. For low-to-medium toughness materials the critical stress intensity factor is given by

$$K_c^2 = \sigma^{*2} \left[\frac{8c}{\pi} \ln \sec \frac{\pi M \sigma_h}{2\sigma^*} \right] \tag{5}$$

whereas for high toughness materials the yield stress formulation

$$\sigma^* = \sigma_h M \tag{6}$$

holds, when the yield stress criterion

$$\left(\frac{K_c}{\sigma_y}\right)^2 / c \geq 7 \tag{7}$$

is satisfied.

Recently, FOLIAS suggested an alternativeformulation, the details of which are given in the Appendix of [2]. For strain-hardening materials his considerations result in the equation

$$K_c^2 = \frac{8 \sigma_h^{*2} c}{\pi} \ln \frac{c_c}{c} \tag{8}$$

where c_e is the distance from the center of the crack to the elastic-plastic zone boundary. The ratio of $\frac{c}{c_e}$ is given by

$$\frac{c}{c_e} \approx 1 - \left(\frac{\sigma_h}{\sigma_b^*}\right)^2 \frac{1 + 1.11\,\frac{c_e^2}{Rt}}{1 + 1.11\,\frac{(c_e - c)^2}{Rt}} \tag{9}$$

where

$$\sigma_b^* = 1.15\,\sigma^* \tag{10}$$

is the biaxial modified yield stress with σ^* expressed by

$$\sigma^* = \frac{3\sigma_y + \sigma_u}{4} \tag{11}$$

in order to take into account the influence of strain-hardening.

Another empirical formulation for axial through-wall cracks in cylinders has been proposed by QUIRK [8]:

$$\sigma_u = \sigma_h \left(1 + Ac + Kc^2\right) \tag{12}$$

The coefficient A depends on the Charpy V-notch energy and on the yield stress. The coefficient K depends on the yield stress and on the curvature of the shell.

4. RESULTS

Figure 2 presents the solutions of Eq's. (1), (2) and (12) which were evaluated with the avarage values of K_c given in Table 1. The agreement with the experimental data points is surprisingly good for large crack lengths. The differences between theory and experiments for smaler crack lengths result mainly from using different failure stress criteria in Eq's (1), (2) and (12). The coefficients of Eq. (12) were taken from Figure 3. However, the dependence of the coefficients on the yield stress and the Charpy V-notch energy could not be confirmed. The discrepancy is, perhaps, due to the fact that the experiments were carried out in the NDT-range. The stress value σ_v in the lower part of Figure 2 represents the highest equivalent intensity of combined stress in the double pipe section at operational conditions (primary and secondary stresses are taken into consideration). The equivalent intensity of combind stress were computed in a computer analysis program for the KNK primary piping system [9].

Figure 4 presents a comparison of the experimental data points with the Eq's. (4), (5), (6) and (8). The failure stress curve computed from Eq. (8) is of particular interest, because of its explicit dependence on the plastic zone size. Eq. (5) was computed with the K_c-value which could only be obtained for experiment No. 2, since Eq. (5) failed for the other experiments. The agreement with the experimental data point is not very good for short crack lengths, as was already observed for the yield stress relationship (Eq. (6)).

5. CONCLUSIONS

The results of the first three experiments on reactor piping specimens with axial through-wall cracks are in good agreement with the theoretical predictions for critical flaw sizes. They also agree with experimental results of other investigators [2, 6, 10]. Although the experiments yielded different K_c-values, they led to failure stress curves, which deviate only little from eachother. These investigations confirm that unstable fracture in the primary coolant pipe system is improbable under operational conditions. The critical crack lengths are so large that failures will manifest themselves by leaking prior to fracture. Moreover, the calculated crack lengths must be regarded as a conservative estimate since the K_c-values increase with temperatures.

Critical crack depths are also impossible as can be shown by using the formulation given by TIFFANY and MASTERS [11]

$$\left(\frac{a}{Q}\right)_{cr} = \frac{1}{1.21\pi}\left(\frac{K_{Ic}}{\sigma}\right)^{2} \qquad (13)$$

where a denotes the critical crack size an Q the crack form parameter. For the conservative assumptions of a semicircular surface flaw and a ratio

$$\frac{K_c}{\sigma_y} \geq 0.4\ \text{in.}^{\frac{1}{2}}$$

one optains a critical crack depth

$$a \geq 2.3\ \text{in.}$$

which is nearly 10 times as large as the wall-thickness, as can be seen in Table 1.

Again these results clearly show, that no critical crack size is to be expected in the piping system of the KNK reactor.

Further investigations are planned in order to study the subcritical crack growth behaviour of the 10 Cr Mo Ni Nb 910 steel.

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Table 1. Summary of Experimental and Calculated Results For 10 Cr Mo Ni Nb 910 Steel Pipes

Experimental Values							Calculated Values					
Exp.No	D	t	c	σ_h	σ_Y	σ_u	$K_c^2 \cdot 10^{-4}$; ksi^2 · in.					c_e in.
	in.	in.	in.	ksi	ksi	ksi	Eq.(1)	Eq.(2)	Eq.(4)	Eq.(8)	Eq.(5)	Eq.(8)
1	8.59	0.33	4.90	12.45	38.5	71.3	4.62	7.22	2.10	1.67	-	7.59
2	8.59	0.32	8.89	5.16	38.5	71.3	3.99	7.20	1.93	2.71	5.79	13.15
3	8.66	0.31	2.34	30.50	38.5	71.3	7.98	10.45	3.76	2.05	-	7.10
Average $K_c^2 \cdot 10^{-4}$, ksi · in. :							5.53	8.30	2.59	2.14	5.79	
K_c, ksi in. :							235	288	161	146	241	

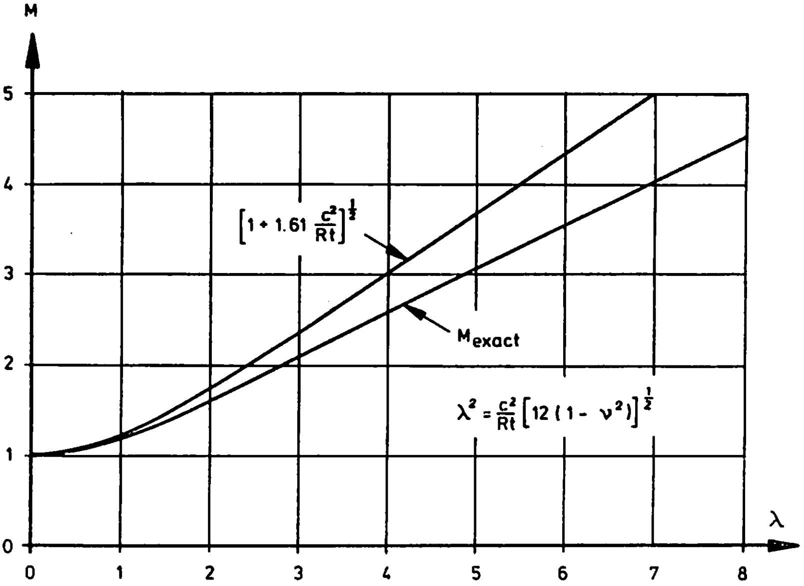

FIGURE 1:

Relationship between λ and stress magnification factor M; Ref. /‾4_7

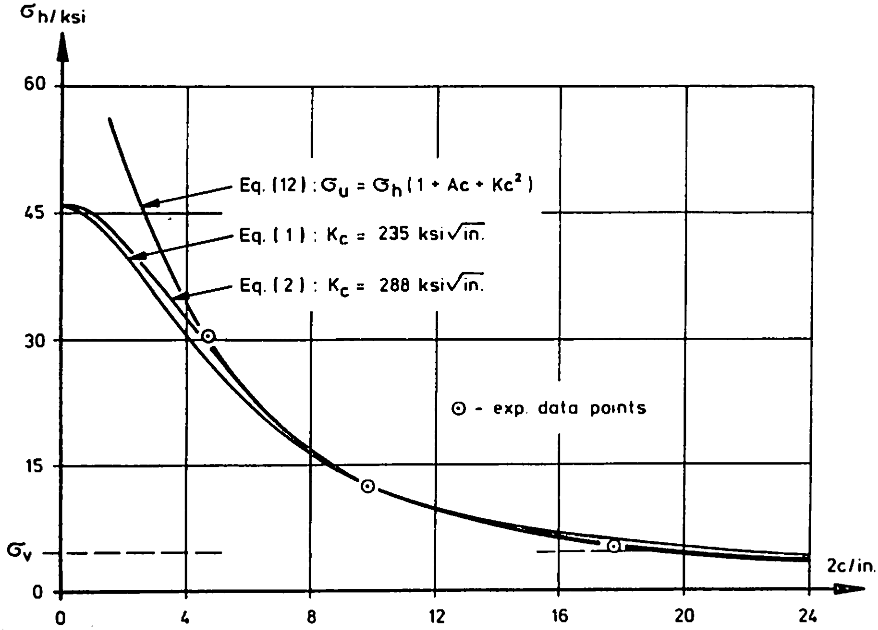

FIGURE 2:

Failure stress curves and experimental data on 10 Cr Mo Ni Nb 910 steel pipes. σ_v for KNK piping system.

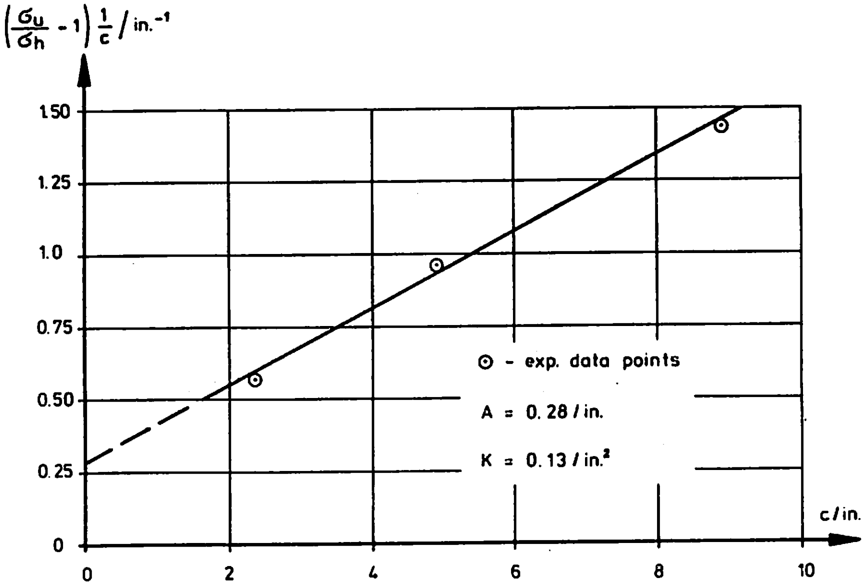

FIGURE 3:

Determination of A and K for 10 Cr Mo Ni Nb 910 steel pipes.

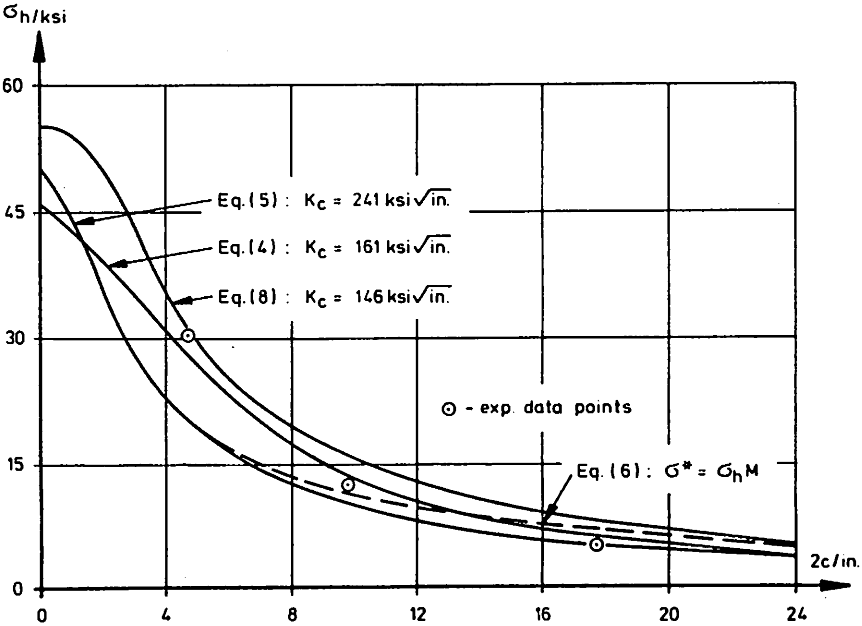

FIGURE 4:

Failure stress curves and experimental data on 10 Cr Mo Ni Nb 910 steel pipes.

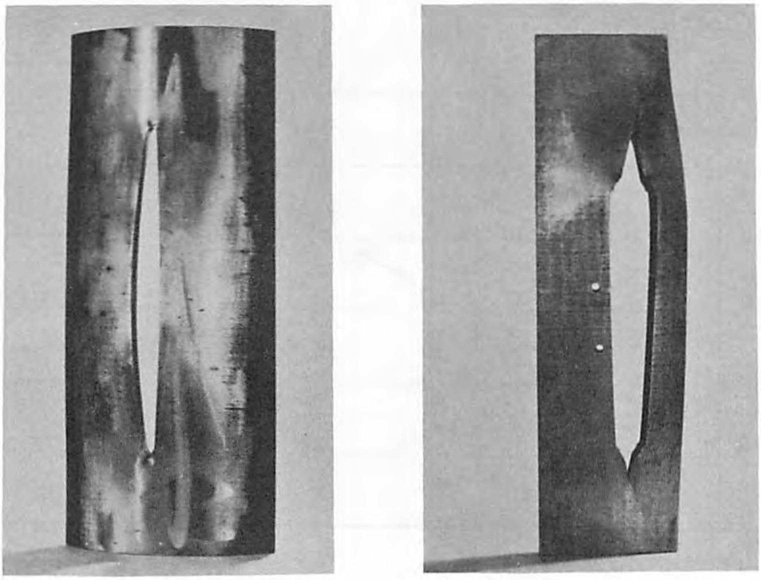

FIGURE 5:

Pipe sections after being cracked.

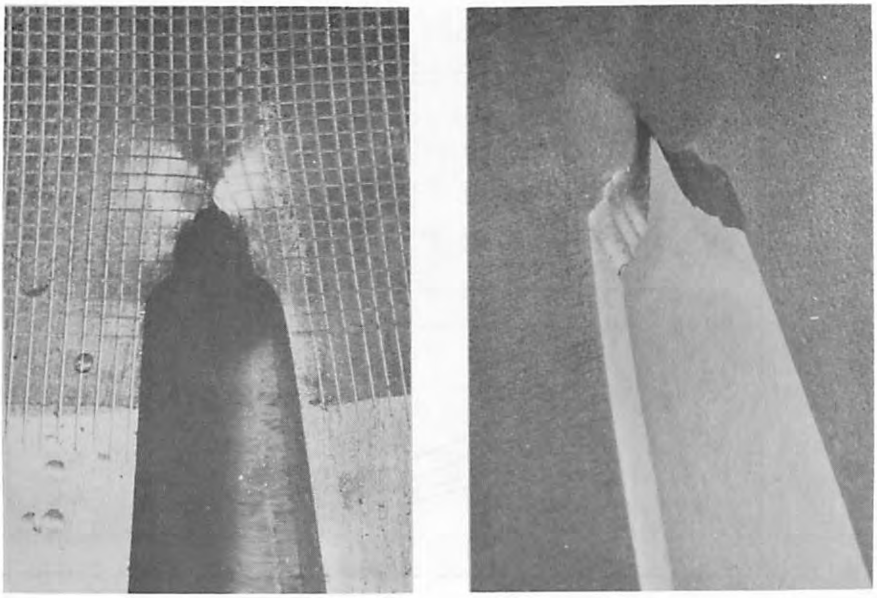

FIGURE 6:

View of crack zone.