# Fracture Behaviour of Cracked AISI 304 s. s. Tubing

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## 1. Introduction

Several fracture criteria have been proposed in the recent years for cracked structures which fracture after a gross plasticity has developed at the crack tip. One may quote for instance several plastic extensions of the fracture toughness criterion [1], the C.O.D. criterion [2] and the flow stress criterion [1].
The tests reported here have been undertaken to determine the most reliable of them for prediction of fracture conditions in AISI 304 (L) tubing containing cracks, in the frame of safety studies relative to the coolant containment of sodium cooled fast reactors. Special attention had to be paid to these particulars consequences deriving from the high ductility and high strain-hardening sensitivity of the material which could make unvalid the available predictions for crack instability.

## 2. Experimental details

Seven 105,4 mm $\phi_i$ - 4,5mm thick and 700mm long tube sections in AISI 304L in which were machined longitudinal cracks of various lengths up to 200mm have been pressurized at constant rate of volume increase till rupture. The crack ends were sharpened with a 0,2mm thick saw, the obtained tip radius being 0,03-0,06mm. Moreover, C.O.D. measurements were done on 3 mm thick S.E.N. tension specimens (fig.1), cut in the transverse direction of the tubes and flattened. (x)

## 3. Results

### 3.1. Cracked tubes

All the tubes evidenced significant stable crack growth and bulging prior to unstable rupture. The shorter the crack, the longer was the crack growth.
Table 1 summarizes the values of gross hoop stress $\sigma_c$ and crack extension length $\Delta 2a$ at instability, and gross stress $\sigma_i$ and C.O.D. $\delta_i$ at crack initiation. An ambiguity exists on the definition of the C.O.D. and on its measurement location due to the gross blunting at the crack tip, an example of which is given at figs. 2 and 3. The measurement standards used here are given in Table 1. The Wells' criterion [3] suggesting to measure at the elastic-plastic boundary seems unapplicable here because too far behind the crack tip. On Table 1 are reported also the values of the flow stress $\bar{\sigma}$ and the fracture toughness $K_c$ calculated for each burst by the relations given by Hahn & al. [1] :

$$\bar{\sigma} = \sigma_c . M \quad (1) \qquad K = \sigma(\pi a \varphi)^{1/2} . M \quad (2)$$

where a : initial half crack length or half crack length at in-tastability; M : magnification factor = f ($\lambda$) with [4]:

$$\lambda^2 = a^2/Rt \cdot (12(1-\nu^2))^{1/2}$$

R,t : radius and thickness; $\nu$ : Poisson's coefficient; $\varphi$ : plasticity correction to crack length:

$$\varphi = \beta^{-2} \, \mathrm{Ln}(\sec\beta)^2 \qquad \text{with} \qquad \beta = \frac{\pi}{2} . \frac{\sigma}{\bar{\sigma}} . M$$

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(x) Further details on the test sections, specimens and instrumentation will be given orally.
The tensile properties of the tubing material are reported in appendix.

and the C.O.D. values at initiation calculated by the relation :

$$\delta = \frac{8\bar{\sigma} a_o}{\pi E} Ln(\sec\beta) = \frac{\sigma^2 \pi a_o}{\bar{\sigma} E} \cdot \varphi \cdot M^2 \qquad (3)$$

where $a_o$ : initial crack length; E : modulus of elasticity; $\varphi$, $\beta$, expressions above where $\sigma = \sigma_i$. This last formula is coherent with the correlation (2) for K if one accepts the basic relation (in plane stress) : $\delta = \frac{K^2}{E\bar{\sigma}}$ and is the same as the Burdekin and Stone expression for the C.O.D. [1] where $\sigma_Y$, the yield stress is replaced by $\bar{\sigma}$, the flow stress, and $\sigma$ by the product of the hoop stress by M. This last correction for curvature appears more justified than the multiplication by the factor $M^2$ of the whole expression [5], which actually represents the correction factor for the first term only of the development of $Ln(\sec\beta)$. In spite of this, the calculated values of $\delta_i$ are much lower than the experimental ones if one takes for $\bar{\sigma}$ a standard value equal to 46kg.mm$^{-2}$ as calculated in the short crack region where it appears as a material constant.

### 3.2. C.O.D. Specimens

Table II summarizes the C.O.D. values at incipient crack growth obtained on the specimens. These are the results of the extrapolation up to the crack tip of the measurements on the whole length of the crack, i.e. 8,3mm. The chosen criterion for the crack growth onset is both the appearance of the crack on the photographs - as for the tubes - and the electrical potential transition [6]. The C.O.D. values do not show significant differences between the fatigue ended cracks and the saw ended craks. The similitude of these values with the $\delta_i$ values measured on the tube is as well prominent. However, due to the questionable character of the C.O.D. measurements on the tube, no conclusion can be presently drawn from this fact.

## 4. Discussion

### 4.1. Instability criterion

The calculated flow stress and $K_c$ values of Table I using both the initial and final crack length clearly show that for the long cracks, $K_c$ is reasonably constant (=523 kg.mm$^{-2}$) while for the short cracks $\bar{\sigma}$ is constant (=46 kg.mm$^{-2}$ on the final crack length basis). The frontier between the two fields may be placed between $2a_o$=25mm and $2a_o$=50mm. It corresponds practically to the condition $\sigma = \sigma_Y$ (=23kg.mm$^{-2}$). Moreover, one can see that this frontier corresponds also to the Hahn & al. criterion [1] in which it is convenient to replace $\sigma_Y$ by $\bar{\sigma}$, i.e. :

$$\left(\frac{K_c}{\bar{\sigma}}\right)^2 \cdot \frac{1}{a} \quad \begin{matrix} > 5 & : \text{flow stress criterion valid} \\ < 5 & : K_c \text{ criterion valid} \end{matrix}$$

The value 5 is obtained combining the relation(2) with the arbitrary limiting condition : $\sigma . M \geqslant 0,9 \cdot \bar{\sigma}$ i.e. $\varphi \sim 2$.
But no conversion of $\bar{\sigma}$ in $\sigma_Y$ is included in the criterion as Hahn does, as the two values are very different for stainless steel and the different correlations between $\bar{\sigma}$ and $\sigma_Y$ proposed by Hahn et al. [1] and Eiber et al. [7] do not apply.
Note that the curve derived from $K_c$ is identical to that derived from $\bar{\sigma}$ in the short crack region: this is because the plasticity correction $\varphi$ in the Hahn et al. correlation has a limit corresponding to $Ln(\sec\beta) \to \infty$ i.e. $\sigma \to \bar{\sigma} . M^{-1}$.





### 4.2. The C.O.D. Approach

The situation is not so convincing for the prediction of crack initiation based on the C.O.D. analysis. In order to get a better agreement between the experimental values of the C.O.D. and those calculated using correlation (3), one was tempted to use in the latter the $\bar{\sigma}$ value corresponding to each crack length. The result is fairly satisfying and evidences once more the influence of strain-hardening. It is clear however that this procedure is unsuitable for predictions. Another possible conclusion would be in the present case to deny to $\delta$ any significance as far as the crack flank displacement is concerned, so giving the correlation (3) exactly the same meaning as K correlation(2). The third possible conclusion is to incriminate the C.O.D. experimental values themselves and one is induced to do so because the large blunting at the tip makes questionable here any up-to-tip extrapolation procedure.

## 5. Conclusions

The reported tests have evidenced the strong influence of the high strain-hardening characterizing austenitic stainless steels which induces to adopt systematically a flow stress instead of the yield stress in every correlation describing the phenomena. However, the previously proposed relationships between $\bar{\sigma}$ and $\sigma_Y$ are of no use for this highly strain hardening material and this is felt to be an interesting field for further reasearch as the above results confirm strongly the validity of the Hahn criteria. Strain-hardening as well as high ductility were certainly determinant to deny significance to the C.O.D. measurements. In this field the development of a reproducible interpolation technique is needed before drawing any conclusion on the feasibility of this approach.

6. Aknowledgements : The experimental assistance of Messrs; MANZOTTI, ROUMENGOUS and TOGNOLI is greatefully aknowledged.

## 7. References

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[3] A.A.Wells - The status of C.O.D. in fracture mechanics 2nd Fracture Mechanics Seminar - ISD Stuttgart 1971
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[5] R.W.Nichols & al."1rst Report of the CODA panel"-Appendix 2-in 'Practical Fracture Mechanics for Structural Steel' UKAEA-Risley-April 1969
[6] J.M.Lowes, J.D.Fearnehoug-Eng.Fract.Mech. 1971-Vol.3pp.103-108
[7] R.J.Eiber & al. - BMI - 1866

### Notes of Table I

(1) The two values reported have been deduced from the last photograph on which crack growth does not appear and from the first one on which it appears. (2) $\delta_i^1$ =values obtained by extrapolation up to the crack tip of the C.O.D. measured on 1mm with a pitch of 0,2 mm. These values are practically equal to these measured at 0,2mm from the crack tip. (3) $\delta_i^{10}$ =idem, on 6-15mm with a pitch of 1mm. (4) Calculated using relation (3), $\bar{\sigma}$ =46kg.mm$^{-2}$ and average between minimum and max.value for $\sigma_i$. (5) In the formula of $K_c$, the value of $\bar{\sigma}$ has been taken as 46 kg/mm$^2$ which is the mean value of the last column in the field $\bar{\sigma}$ = constant.

TABLE I: Burst tests results

(See notes at the bottom of page 3)

| $2a_o$ (mm) | Initiation (1) $\sigma_i$ (kg/mm$^2$) | $\delta_i^1$ (2) ($\mu$) | $\delta_i^{10}$ (3) ($\mu$) | (4) $\delta_i^{th}$ | Instability $\sigma_c$ kg.mm$^{-2}$ | $\Delta(2a)$ (mm) | Calculations based on: a = $a_o$ $K_c$(5) kg/mm$^{3/2}$ | a = $a_o$ $\bar{\sigma}$ kg.mm$^{-2}$ | a=$a_o$+$\Delta$a $K_c$ kg/mm$^{3/2}$ | a=$a_o$+$\Delta$a $\bar{\sigma}$ kg.mm$^{-2}$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | --- | --- | --- | -- | 52,3 | -- | -- | 52,3 | - | 52,3 | calculated with original thickness and diam. |
| 15,9 | 28,9-30,3 | 560-580 | 1340-1350 | 48 | 34,7 | 10 | | 41,6 | | 48,3 | $\bar{\sigma}$ const. |
| 25,0 | 23,7-24,9 | 480-590 | 1600-2160 | 65 | 27,5 | (5-15) | | 38,2 | - | (41,8-48,8) | |
| 50,0 | 18,4-20,3 | 420-920 | 1480-2260 | 248 | 21,2 | 4 | 569 | 44,6 | 546 | 46,3 | |
| 75,4 | 12,7-13,4 | 730-1300 | 1260-1960 | 261 | 13,6 | 5 | 531 | 38,8 | 525 | 39,6 | $K_c$ const. |
| 100 | 9,30-9,80 | 690-X | 1170-X | 251 | 9,80 | ( 26) | 472 | 34,3 | - | - | |
| 150,2 | 5,86-5,93 | 720-1000 | 1440-1780 | 262 | 6,02 | 2 | 507 | 29,8 | 497 | 29,5 | |
| 200 | --- | --- | --- | - | 4,30 | (12) | 531 | 27,5 | - | - | |

Table II

C.O.D.($\mu$) at incipient stable crack growth on S.E.N. specimens

| | | Saw ended cracks 2 | 3 | 5 | Fatigue ended cracks 1F | 2F | 3F |
|---|---|---|---|---|---|---|---|
| Criterion for crack initiation | Electr. potent. transit. | 580 | 720 | 625 | 500 | no transition detected | |
| | Optical avidence | 540-640 | 570-670 | 700 | 850-1120 | 405-505 | 580-675 |

Appendix

Tensile properties of the AISI 304L tubing

| | $\sigma_{0,2}$ | $\sigma_R$ | A% | Remarks |
|---|---|---|---|---|
| Longit. specimens | 19 | 51,4 | 59 | A% measured on 5,65 s |
| Transverse flattened specimens | 27 | 56,3 | 66 | A% measured on 8,5 s |
| Pressur. tube (hoop direction) | 23 kg/mm$^2$ | 52,3* kg/mm$^2$ | 27%** | * on the basis of the initial dimensions ** meas. on the whole circ. |





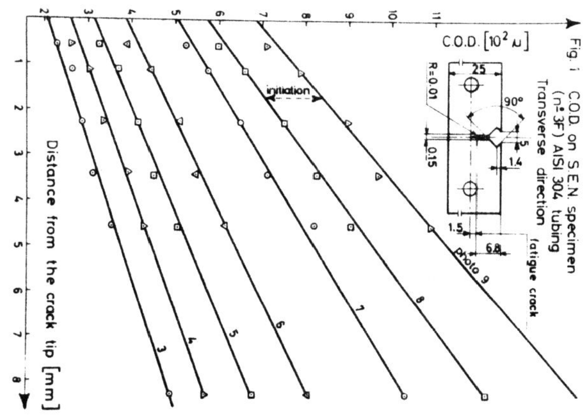

Fig. 1 C.O.D. on S.E.N. specimen (n° 3F) AISI 304 tubing Transverse direction

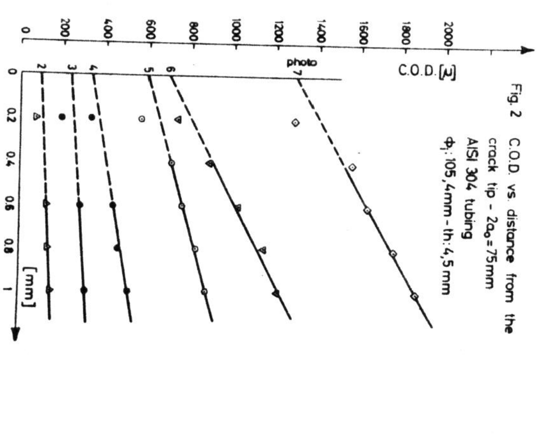

Fig. 2 C.O.D. vs. distance from the crack tip - $2a_o$=75mm AISI 304 tubing $\phi_i$: 105,4mm - th: 4,5 mm

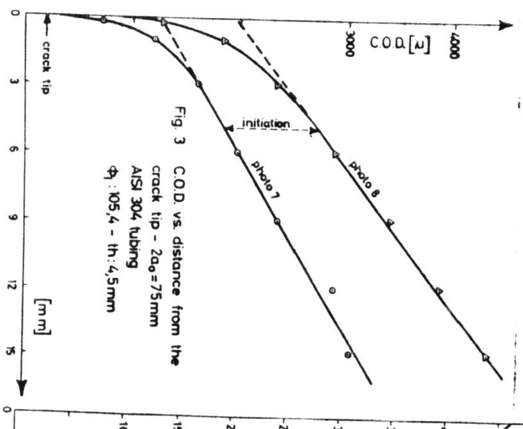

Fig. 3 C.O.D. vs. distance from the crack tip - $2a_o$=75mm AISI 304 tubing $\phi_i$: 105,4 - th: 4,5mm

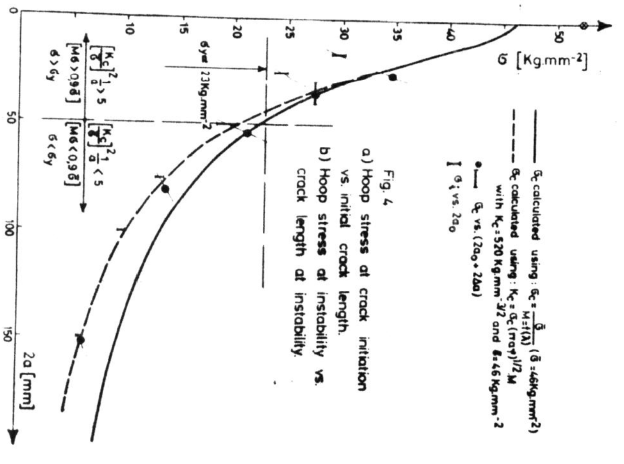

Fig. 4 a) Hoop stress at crack initiation vs. initial crack length. b) Hoop stress at instability vs. crack length at instability.