INFLUENCE OF SPECIMEN GEOMETRY ON THE FRACTURE TOUGHNESS DETERMINATION OF AN AUSTENITIC STAINLESS STEEL TUBE.

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The fracture toughness of cold rolled stainless steel tubes has been determined by using different types of specimens. Three-point bend specimens with different crack orientations are compared with CT--specimens with the crack oriented in the longitudinal direction of the tube . The influence of different initial fatigue crack lengths ranging from a/w = 0.50 to about 0.70, has been investigated for three-point bend specimens with different crack orientations.

The J value, as determined from longitudinal three-point bend specimens is higher than the J_{IC}-values obtained from specimens in transverse directions. Transverse specimens with different crack orientations give approximately equal J_{IC} values but different values of dJ/da. These differences are discussed.

A higher a/w-value yields lower J_{IC} -values for transverse three-point bend specimens with a radial crack orientation but the ratio a/w has no significant influence on the J_{IC} value for transverse three-point bend specimens with axial crack orientation.

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1. Introduction

Very few components in applied situations have a geometry which is suitable for direct determination of fracture toughness. Furthermore the size of the component is often a factor which limits the dimensions of fracture toughness specimens.

Previous work on steel tubes has been performed by e.g. Nyilas and Krauth (1) and Garwood and Archer (2). The present study is concerned with the determination of fracture toughness in tubes of 90 mm diameter and 19 mm wall thickness. Since the toughness of the tube material is high, a determination using standard fracture toughness specimens is not possible for all crack orientations. In addition, anisotropic mechanical properties require the use of specimens with crack planes in different directions. Therefore, the results and the test methods have to be critically examined.

2. Experimental details

The material used in the present investigation was taken from a pilot melt of cold worked tubes of a 27Cr-31Ni austenitic stainless steel. As shown in Fig. 1 five different types of specimens were considered, namely 3 types of three-point bend specimens, a modified CT specimen and a semi-lunar specimen termed SL. The three point bend specimens were sectioned from the tube wall in such a way that three different crack orientations could be studied.

Three-point bend specimens had the dimensions 5 mm x 10 mm x 50 mm. SL specimens were chosen because their ligament correspond to the entire wall thickness and can therefore be expected to yield more representative results. However, the SL geometry is essentially a three-point bend geometry with the dimensions 9.5 mm x 10 mm x 74 mm at the largest section and a span of 65 mm. CT specimens, having the outer wall surface in the original condition and the inner surface machined flat, had the dimensions 19 mm x 45.6 mm x 47.5 mm. For these specimens care was taken to maintain the inner surface close to the notch in its original condition.

With the exception that specimen geometries were not standard for SL and CT specimens, testing was performed at room temperature according to the ASTM E813 scheme at two different laboratories. Comparison between results obtained for similar specimens showed that there was no significant difference between the two laboratories.

Evaluation of the CT-results were based on the thickest section and the actual load displacement curve. This deviation from ASTM conditions is thought to be of minor import-

ance. However, it was considered to be an essential requirement since it is known that the surface and bulk properties differ markedly. The displacement in the P- Δ curves was determined using LVDT:S, which were not directly attached to the deflection between rollers. The J-values were corrected by subtracting the contribution from the compliance of the testing equipment. This was made by recording the load-displacement curve for a stiff brick-type specimen.

The fatigue crack length, a , and the crack growth, Δ a, were both determined from measurements on 9 equispaced points as suggested by Clarke et al (3). The effective yield strength of the tube wall was determined to 875 MPa in the transverse direction and 975 MPa in the longitudinal direction. Effective yield strength was defined as the mean value of Rp0.2 and Rm.

3. Results

The results from fracture toughness measurements are shown in Table 1 below:

Table 1 (For specimen designation see Fig. 1)

	L-R	SL	T-R	T-L	CT
J_{IC} (kJ/m^2)	134*	110	75	86	94
T-modulus	255	110	113	43	1.2

* This value of J is not a valid result according to ASTM 813.

It can be inferred from this table that there are rather small differences in J_{IC} between different specimen types, although it appears that the resistance to crack initiation is significantly higher for longitudinal specimens. In contrast to J_{IC}, the T-modulus exhibits large variations, ranging from 1.2 to 255.

Figure 2 is a graphical representation of results for the two types of transverse three point bend specimens and SL specimens. It is evident from this diagram that the resistance to crack growth is higher for radial crack orientations (SL, T-R) than for a longitudinal crack orientation. However, the corresponding values of J_{IC} do not differ significantly.

It was expected that T-L and modified CT-specimens would behave similarly, since they have their crack planes in the same orientation. This is true regarding initiation but certainly not regarding crack growth as shown in Fig. 3. It can be concluded from this diagram that once a crack is initiated in the CT-specimen it can propagate much easier than in a T-L specimen. This fact is a consequence of the CT geometry which is different from that of the three-point bend specimen. Similar effects have been observed by Jones et al (4). It is unlikely that this large effect is due to the modification of the CT specimen. It should be pointed out in this context that the material was inhomogeneous through the wall since the degree of cold work was considerably higher in the surface regions. In CT specimens the crack goes through both bulk and surface material whereas three-point bend specimens represent only the bulk of the material.

As shown in Fig. 4 there is a problem associated with testing of L-R specimens. The resistance to crack growth is so high that the requirement

$$\frac{dJ}{da} < \sigma y$$

is not satisfied. An implication of this is that it has proved impossible to obtain a sufficient number of data points between the offset lines.

An attempt was made to investigate the role of fatigue precrack length on the J_{IC}-values. T-R and T-L specimens having crack lengths ranging from 5 to 7 mm were tested. Since ASTM E813 prescribes cracks in the interval 5-7.5 mm for this specimen size all cracks considered were acceptable according to this standard. Each specimen was loaded to incipient crack growth as defined by a maximum load criterion. All specimens exhibited signs of crack growth but the growth was always less than 0.14 mm. The data points for T-R specimens, which are shown in Fig. 5 each represent one test specimen. They show a declining tendency of J_{IC} with increasing crack length. This effect was not observed in T-L specimens. However, Vassilaros et al (5) and de Castro (6), have reported that the J_{IC}-value is dependent upon crack length, even though fatigue pre-cracks valid according to ASTM E813 were used. It is also interesting to note that for T-L and CT, an T-R and SL respectively, the J_{IC} value is higher for the largest cross sections and remaining ligaments, i.e. for the smallest degree of plastic behaviour.

A metallographic study of the microstructure showed that there was a marked elongation of grains in the longitudinal direction of the tube (Fig. 6). Examination of transverse sections of the tube wall showed that the grains were virtually equiaxed in transverse planes, an example of which is given in Fig. 7.

4. Discussion of test method and results

As is seen in the result section, there is a clear difference in toughness between the longitudinal and the transverse modes. This is related to the micro-structure of a cold worked tube, in which the grains and inclusions are elongated in the longitudinal direction. The high toughness of L-R specimens can be explained if it is assumed that grain boundaries serve as barriers to plastic deformation, since the crack experiences a high density of boundaries in this direction. Moreover, there is reason to believe that the orientation of the crack plane in L-R specimens in relation to the elongated inclusions is more favourable. In fact, it can be argued that the material behaves like a composite material in this respect (7).

The J_{IC}-value for L-R specimens is so high that the conditions of ASTM E813 are not completely fulfilled. In our estimation J_{IC} is around 130 kJ/m^2 for L-R specimens and around 80 kJ/m^2 for T-R and T-L specimens. It is also noteable that an intermediate value of 110 kJ/m^2 is obtained for SL specimens.

The use of several specimens for each J versus Δa curve gives rise to statistical scatter which does not occur in the single specimen method. Depending on material and preparation each test represents a curve J versus Δa with its own J_{IC} and T-value.

Both J_{IC} and T are statistically distributed. When only one point is used on each curve, as in the multi-specimen method, the effect of statistical scatter may be increased as indicated in Fig. 8. Depending on how a sample of results (Fig. 8a) is divided into two sets of results for (valid) evaluation (Figs. 8b and c), the uncertainty may appear worse than the "true" scatter gives reason to suppose. This has been discussed by e.g. Landes and Begley (8). In the standard ASTM E813 both single and multispecimen alternatives are allowed.

In the present investigation the importance of scaling effects can be neglected, since the full section of the tube material is used for testing. We use results from test specimens in general yielding, and hence the peculiarities of yielding fracture mechanics should be considered. Firstly, in general yielding, the constraint at the crack tip changes with specimen geometry as has been shown by e.g. Hancock and Cowling (9). Thus the relationship between strain and stress at the crack tip and the value of J changes. Therefore most of the results of this investigation are valid only for a loading condition corresponding to e.g. flattening. In the case of a cracked tube loaded by hydraulic pressure another mode applies.

Secondly, it is important to observe the definition of J in the standard ASTM E813 in relationship to the J definition for a growing crack consistent with a fracture criterion of strain or deformation type as pointed out by Rice et al (10). In this case of pure bending, it is apparent that

$$J = \frac{2 \int P d\delta}{B\ (w-a)}$$

is not consistent with a correct J-definition. For small crack growth increments the practical errors can be considered small. It is also remarked that the J_{IC}-value registered in a case like this does not correspond to the J_{IC}-value obtained by

$$J_{IC} = K_{IC}^2\ (1-\nu^2)\ /\ E$$

from a test on a large specimen, where the small scale yielding approximation is valid and unstable fracture occurs within the realms of LEFM, but after a maximum of stable crack growth. In the present case the values should be smaller than small scale yielding results. See also Fig. 5 where a dependence of J_{IC} of a/w relationship is shown, which may be due to a varying degree of plasticity at initiation.

More important in this case are the variations obtained in the apparent T-value (apart from statistical scatter). As is seen from the result section, strongly varying results are obtained for different test geometries. Here, these differences are discussed in general terms only for the bending mode.

In the original interpretation of the J-R curve T is a function of Δa and tends to zero when the stationary case is approached as shown by Andersson and Broberg (11, 12). In contrast to this, T in general yielding fracture mechanics is supposed to be a constant within the limit of crack growth acceptable for an approximate J-evaluation. It should then be noted that theoretical considerations (10) indicate that this "T_{mat}" is not a material constant, or equal to the start of the slope of the real J-R curve for small scale yielding. Instead it is in general a function of the relationship a/w and $\sigma y/E$. For high T-values the importance is not very great. In this case the difference in T between a/w = 0.5 and a/w = 0.7 (for $\sigma y/E$ = 0.003-0.004, and w=10 mm and grain size of 50 µm) should theoretically be of the order of 10. This difference is small in comparison with the scatter of the present test results although there is a tendency for T to decrease with increasing a/w. This is in agreement with other results (5, 6), which however relate to other test geometries. As in the case of J_{IC}, T should therefore be evaluated and used only as an approximate value for instability analysis.

Finally, the limits for crack growth in ASTM E813 are given in absolute terms, 0.15-1.5 mm, and they are not related to grain size or specimen size. Just as in fatigue problems, the size relationships play an important role. In this case, where very small specimens have been used, and crack growth therefore is limited in relation to ligament width it is revealed that the present standard limits have been chosen with reference to a limited range of material properties and test specimen sizes. This fact should be observed when non-standard tests are made, e.g. when very large values of Δa are used (5-10 mm). For the approximate evaluation of J_{IC} in the present case a cluster of points near the blunting line of initiation should be preferred also with regard to the uncertainty in T-evaluation and the multi-specimen method.

5. Conclusions

J_{IC} has been shown to be a function of the crack plane orientation.

J_{IC} exhibits a weak dependence upon a/w.

The main uncertainties of the results are inherent in the method and the extreme choice of test specimen size. Yet, the results appear to give approximate values of J_{IC} for this tube dimension and mode of loading.

It has been possible to demonstrate experimentally some of the theoretical uncertainties of the method, particularly that T is not a material parameter, but that it is dependent on specimen geometry. For high toughness materials this does not have a significant effect and the T-analysis could be used as a complement to plastic limit load analysis in cracked structures.

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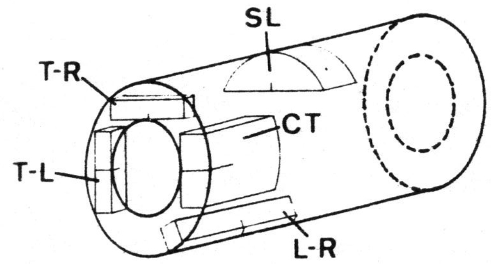

Fig. 1 Schematic illustration of specimen types used.
Three-point bend specimens: 5 x 10 x 50 mm
SL-specimen mid-section: 9.5 x 19 mm
CT-specimen mid-section width equal to wall thickness

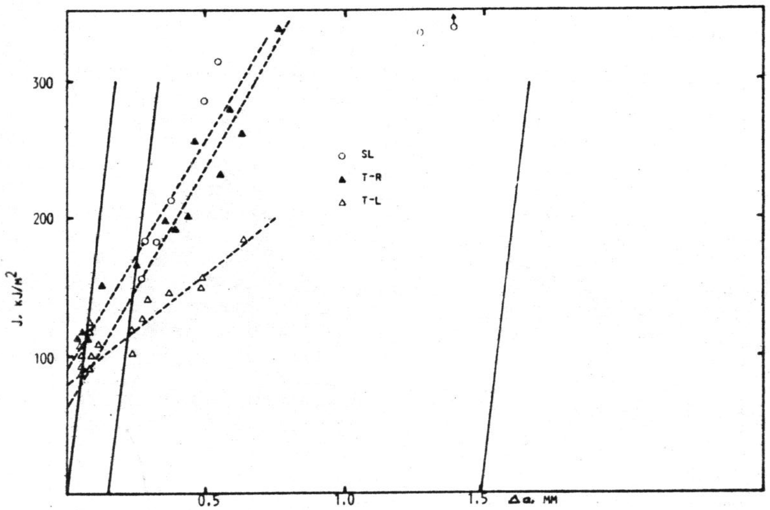

Fig. 2 J-Δa diagram showing results from SL, T-R and T-L specimens

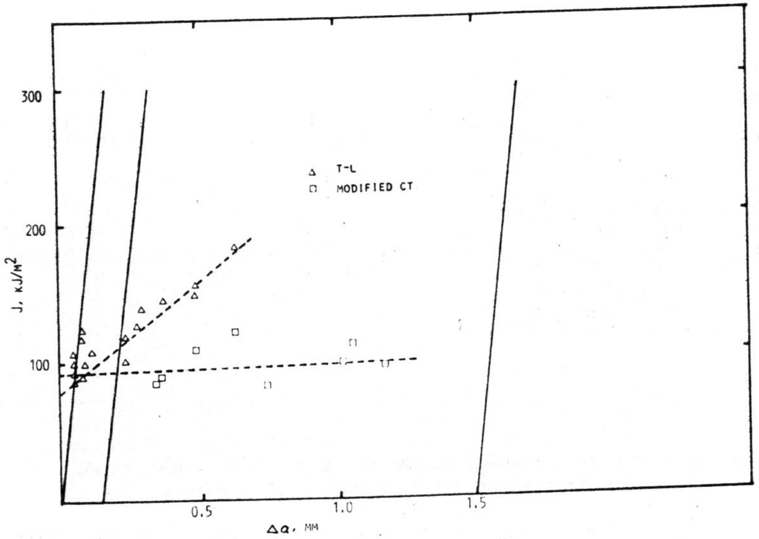

Fig. 3 J-Δa diagram showing results from T-L and CT specimens

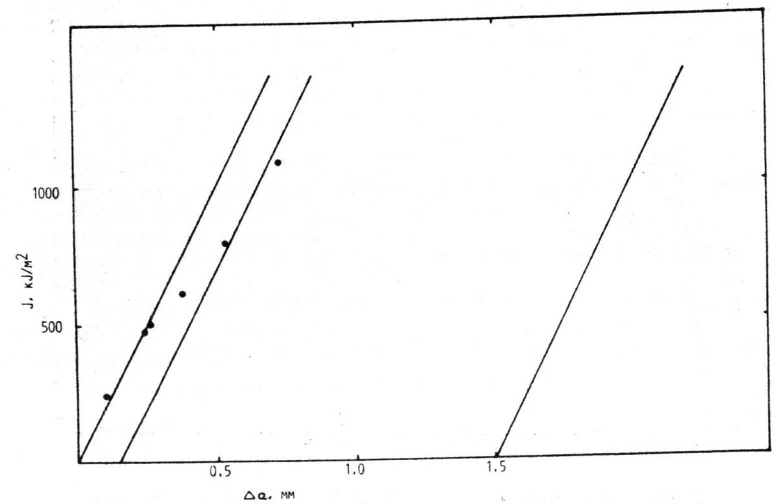

Fig. 4 J-Δa diagram showing results from L-R specimens

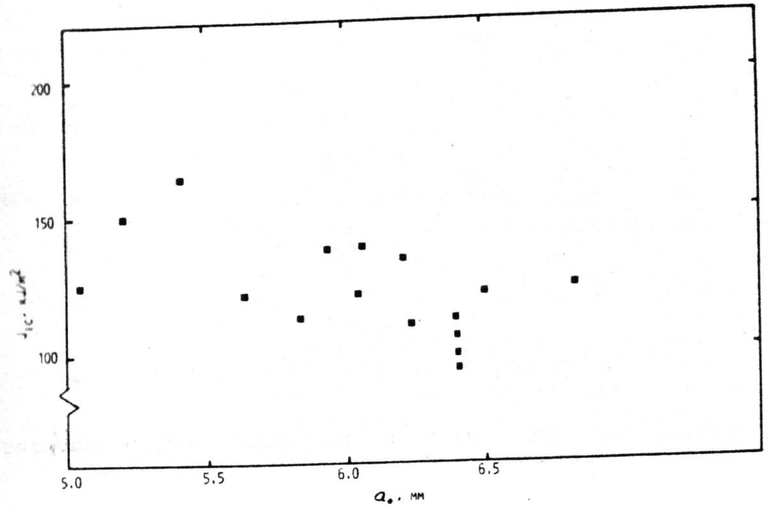

Fig. 5 Diagram showing a declining tendency of J_{IC} with pre-crack length

Fig. 6 Optical micrograph showing elongation of grains in the longitudinal direction (arrowed). M = 100X

Fig. 7 Optical micrograph of a transverse section showing equiaxed grains. M = 200X

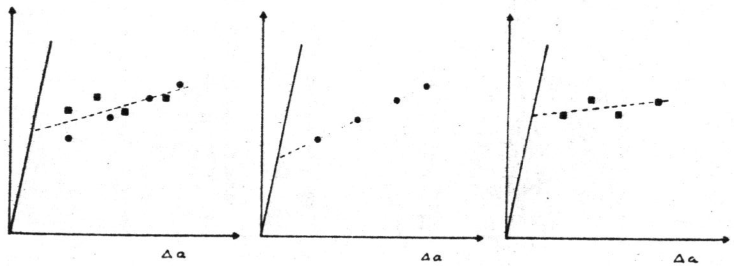

Fig. 8 A set of 8 fictitous data points shown in a. These can be divided into two subsets of points as in b and c, resulting in considerable differences in J_{IC} and T.