IMPROVED METHODOLOGY TO DETERMINE LOWER BOUND HAZ CTOD TOUGHNESS

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Presently only a few crude rules exist for the assessment of HAZ fracture toughness. They are all based on a microstructural validation of each specimen after the test. Because of the difficulty to obtain valid results many tests are performed in vain. Furthermore, the existing rules do not yield statistically defined lower bound estimates of the HAZ fracture toughness. Here, a new more efficient methodology, for evaluating CTOD toughness of HAZ with respect to assessment of local brittle zones, is presented based on statistical modelling.

INTRODUCTION

A critical topic in offshore and natural gas structures is how to evaluate the fracture toughness of the weld heat affected zone (HAZ). Present testing standards are purely directed towards testing of plate material. A few procedures for evaluating HAZ fracture toughness have been proposed by e.g. API and other organizations connected to the oil industry. A common denominator of the procedures is that they include comparatively severe requirements for when a test is to be considered valid. This leads to a large number of rejected tests, thus, increasing the costs of testing. Furthermore, the procedures are mainly based on empirical assumptions, due to which they are not very reliable.

Normally CTOD test results in themselves show a considerable scatter, especially in the case of cleavage fracture. The scatter is large even for homogeneous materials, but in the case of inhomogeneous materials, like the HAZ in welds, the scatter can be intensified. This is especially the case if the HAZ contains local brittle microstructures. In such cases the CTOD value will

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depend on the probability that the crack front contains such brittle microstructures. Presently most guidelines to assess HAZ toughness contains a validation procedure of the test results, based on sectioning and microscopic examination of the fractured specimens.

Due to the difficulties associated with the positioning of the fatigue crack tip, many tests are judged as invalid. Thus, HAZ testing can be both inefficient as well as expensive. In the present paper, application of a statistical cleavage fracture model enables the development of more flexible rules for the assessment of HAZ fracture toughness. A new improved methodology for analyzing CTOD test results of HAZ with respect to assessment of local brittle zones is presented, based on a statistical treatment.

GUIDELINES TO EVALUATE HAZ-TOUGHNESS

In the case of brittle cleavage fracture (i.e. δ_c) several statistical models (Wallin (1)) yield a simple equation for the scatter of fracture toughness. For δ_c the equation can be expressed as

$$\delta_c = \delta_0 \cdot \left\{\ln\frac{1}{1-P}\right\}^{1/2} \qquad \text{..(1)}$$

where δ_0 is a normalization parameter corresponding to a specimen thickness B_0 (ie. crack front length). The normalization parameter represents a failure probability of 63.2 % and is related to the median fracture toughness $\delta_{.5}$ by $\delta_{.5} = \sqrt{\ln 2} \cdot \delta_0$.

Equation 1 has been comparatively well validated for a large number of materials failing by cleavage fracture (1).

Using a model corresponding to equation 1, Nevasmaa and Wallin (2) have shown that if the HAZ contains local brittle zones (LBZ) that are more than 3 times more brittle than the matrix, then the LBZ microstructure determine the behavior of the whole specimen. Thus it is sufficient to investigate the LBZ microstructure.

Within a Nordic project (Hauge and Thaulow (3)), the behavior of the minimum measured CTOD value, as a function of total length of LBZ, has been studied, based on the same theory as above. Based on this study a methodology to obtain lower bound estimates of the fracture resistance has been developed.

The methodology uses the minimum measured CTOD value, to determine if the material should be considered brittle. It is based on a statistical method for hypothesis testing where a selected characteristic CTOD value δ_P associated with a failure probability fractile P and a crack front length B_0 consisting only of the microstructure in question. According to the binomial distribution, the probability P_{min} that an arbitrary CTOD value will be lower than the minimum of N tests is given by

$$P_{min} = 1 - (1 - P_{conf})^{1/N} \qquad \text{...(2)}$$

where P_{conf} is the desired confidence level. In order to include the amount of LBZ sampled by the crack front, a number N_{eff} is defined to express the total length of LBZ sampled by the crack for all tests Σl_i divided by the crack front length for the specimens.

$$N_{eff} = \Sigma l_i / B_0 \qquad \text{...(3)}$$

By replacing N with N_{eff} in equation 2, all specimens where l_i is greater than zero will contribute to the statistical basis for determination of P_{min}. Thus all specimens are "valid" regardless of the amount of sampled LBZ along the crack front. This feature makes the testing more efficient and economical.

P and δ_P correspond to a point at the distribution function given in equation (1). This is also the case for P_{min} and a corresponding minimum CTOD δ_{min}. The value of δ_{min} is determined by combining equations 1 through 3.

$$\delta_{min} = \left\{ \frac{\ln\frac{1}{1-P_{min}}}{\ln\frac{1}{1-P}} \right\}^{1/2} \cdot \delta_P \qquad \text{...(4)}$$

A minimum CTOD value greater than δ_{min} will verify the assumption of δ_P as the P-fractile of the CTOD distribution for specimens consisting only of the LBZ microstructure along the crack front. Two examples of the use of equation 4 are presented in figures 1 and 2. Figure 1 is based on the mean length of microstructure (l_i), whereas Figure 2 is based on the total length of microstructure (Σl_i). Both figures are based on a 75 % confidence level and a 10 % lower toughness fractile corresponding to $\delta_P = 0.1$ mm. Similar figures can be developed for any desired fractile and confidence level. These guidelines can be directly used for determining toughness criteria for welded structures.

VERIFICATION

The Nordic project (3) produced a considerable amount of HAZ CTOD data generated at four different laboratories (Osaka University, in Japan, The Technical Research Centre of Finland - VTT, in Finland and The Danish Technological Institute and RISØ, in Denmark). Two different steels, one Japanese and one Danish, were welded in each country with two different heat inputs, a High and a Low. The welding procedures were similar in each country, but not identical. Especially the Japanese welding procedure for the low heat input differed from the others. Thus slight differences in the fracture resistance of the different weldments are to be expected. The differences in the fracture resistance of the HAZ is not, however, likely to be significant, in view of the inherent scatter of brittle fracture CTOD.

The different laboratories used test specimens of varying sizes, ranging from a thickness of 22 mm to a thickness of 50 mm equal to the full plate thickness. The HAZ were tested both in the through thickness as well as the surface direction. In the case of surface notched specimens, the crack depth a/W varied in the range 0.25 → 0.6. Due to the differences in the specimens, the data sets were treated as separate (but similar) sets of data. After testing, the majority of the specimens were sectioned and the microstructures along the fatigue crack tip were identified.

Unfortunately, many results were affected by large scale yielding. Since large scale yielding is dependent upon specimen size and since a CTOD value affected by large scale yielding does not represent a "true" fracture resistance value, no attempts were made to determine the fracture resistance distributions based on the experimental data sets. Instead a different approach was used.

In the analysis of the CTOD data, equation 4 was applied to compare the minimum CTOD values for the different data sets. The model indicates that the minimum measured CTOD should be directly proportional to $(\Sigma l_i)^{-1/2}$.

For the analysis, the length of the coarse grained microstructure was assumed to correspond to the length of the LBZ. Only the data for which the microstructures had been determined were included in the analysis. The results have been compiled into Figures 3 and 4 and Table 1. Figure 3 shows the results corresponding to the Japanese steel and Figure 4 corresponds to the Danish steel. The lines in the figures are drawn to be directly proportional to $(\Sigma l_i)^{-1/2}$. The results comply well with the theoretical behavior. The results from Osaka University are slightly higher than the others, but this can well be attributed to the different welding procedure and to the different definition of coarse grained microstructure used by them. As a whole the CTOD results seem to verify the validity of equation 4.

In Table 1 is also included the calculated lower bound δ_p corresponding to 10 % fractile with a 75 % confidence and a B_0 equal to 50 mm.

APPLICATION TO TOUGHNESS ASSESSMENT

If acceptance criteria for CTOD results are defined and these criteria refers to the case of only LBZ along the crack front, the above model can be applied directly. However, such conditions rarely occurs for structural steel weldments. In order to relate δ_P to situations where only parts of the crack front consists of the LBZ microstructure, the statistical crack front length effect can be utilized. Equation 1 yields

$$\delta_{Pl} = \delta_P \cdot (B_0/l)^{1/2} \qquad \text{...(5)}$$

where δ_P corresponds to a sampled length of LBZ equal to the crack front length B_0 and δ_{Pl} corresponds to a sampled length of LBZ equal to l. Equation 5 is termed the statistical crack front length correction and it can be applied in order to relate the results to more realistic conditions with respect to sampled length of LBZ. Table 1 shows an application of equation 5 for comparison of different data sets. Equation 4 has been inverted as to yield δ_P from the measured minimum CTOD value. Equation 5 has been subsequently used to determine an equivalent δ_P^{50mm} for the case of a 50 mm thick specimen. With some exceptions for data sets with very few data points and the Osaka data where the definition of LBZ probably was somewhat different, Table 1 shows quite consistent results with values around 0.021 mm for the Japanese steel and around 0.014 mm for the Danish steel.

Another application of equation 5 is to modify the characteristic value for the conditions in a structural component. In this way the fracture toughness value to be applied in a fracture mechanics assessment can be related to more realistic conditions and the degree of conservatism associated with the assumption of 100 % hit of LBZ can be reduced. However, information (or assumption) on the sampled amount of LBZ has to be provided. In the results in Table 1, between 30 % and 70 % of the crack front consisted of LBZ. If these results are assumed to be representative for real structures, equation 5 yields that the characteristic fracture toughness can be increased by a factor in the range 1.2 to 1.8 for B_0/l equal to 0.7 and 0.3 respectively.

SUMMARY AND CONCLUSIONS

If a brittle microstructure has been identified in HAZ of a weldment and if this microstructure (denoted local brittle zone - LBZ) represents the major initiation locations for brittle fracture, the minimum CTOD value can be applied to determine the lower bound fracture toughness. In addition to the minimum CTOD value, the described method takes into account the number of tests (and subsequently the information that all the other tests gave higher CTOD values than the minimum) and the amount of LBZ sampled by the crack front on the specimens.

The results indicate that the demand for full thickness specimens, presently in use in existing guidelines and test standards, is not necessary with respect to the lower bound fracture condition. Consistent results were obtained with subsized specimens as long as the total amount of sampled LBZ was the same.

The method is demonstrated to be applicable for implementation in specifications where acceptance criteria are defined in a statistical format. Characteristic values for fracture toughness corresponding to a specified fractile and confidence level can be determined.

The characteristic values can be modified in accordance with the different conditions occurring in other test results (for comparison) and in structures (for structural integrity evaluations). The statistical crack front length effect provides this modification both for the crack front length and for the amount of sampled LBZ.

TABLE 1 - Summary of HAZ CTOD results.

JAPANESE	STEEL $T = -80$ °C				$P = 0.1$	$P_{conf} = 0.75$
LAB.	TYPE	Σl_{CG} (mm)	N	B (mm)	δ_{min} (mm)	δ_p^{50mm} (mm)
Osaka	L(T)	188.6	19	22	0.09	0.048
	L(S)	275.1	11	50	0.05	0.032
	L(S)	214.6	15	22	0.06	0.034
VTT	L(T)	342.8	41	25	0.03	0.022
	H(T)	650.3	45	25	0.02	0.020
DTI	L(T)	86.9	4	48	0.08	0.029
	L(S)	48.0	1	48	0.56	0.148
	H(T)	175.7	6	48	0.04	0.021
	H(S)	96.0	2	48	0.04	0.015
RISØ	L(T)	70.7	5	45	0.20	0.066
DANISH	STEEL $T = -60$ °C				$P = 0.1$	$P_{conf} = 0.75$
LAB.	TYPE	Σl_{CG} (mm)	N	B (mm)	δ_{min} (mm)	δ_p^{50mm} (mm)
DTI	L(T)	73.0	5	48	0.036	0.012
	H(T)	171.8	5	48	0.027	0.014
	H(S)	51.4	2	48	0.052	0.015
RISØ	L(T)	18.0	1	45	0.251	0.042
$T = -80$ °C	L(T)	83.3	5	45	0.032	0.011

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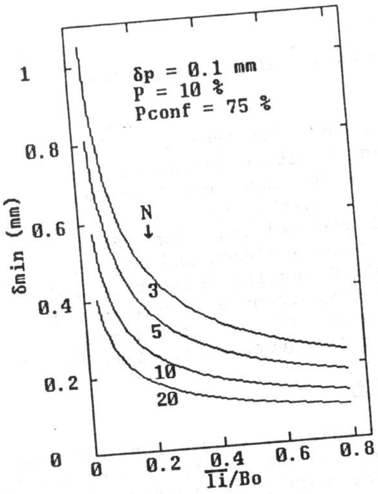

Figure 1 Requirement for minimum CTOD based on mean length of LBZ

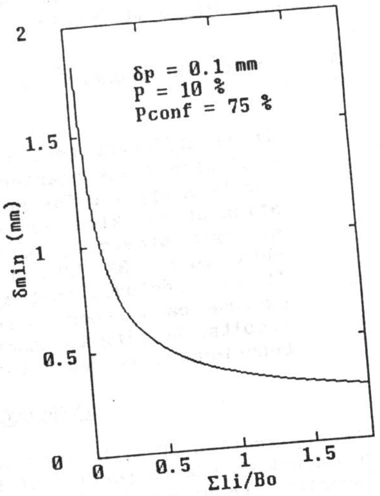

Figure 2 Requirement for minimum CTOD based on total length of LBZ

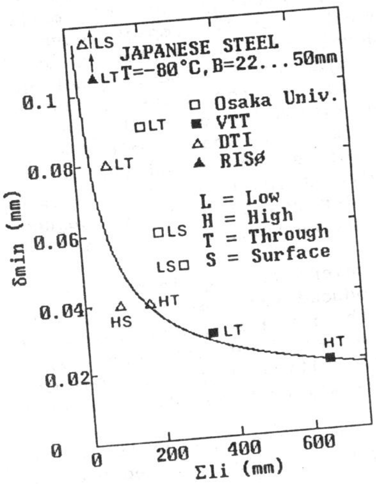

Figure 3 Minimum CTOD vs total amount of CG for Japanese steel

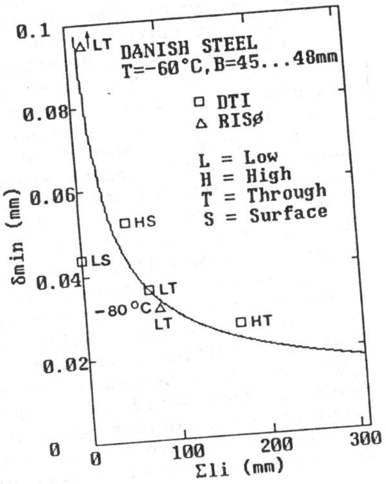

Figure 4 Minimum CTOD vs total amount of CG for Danish steel