A NOVEL METHOD FOR FRACTURE TOUGHNESS ASSESSMENT OF INHOMOGENEOUS FERRITIC STEEL WELDMENTS USING BIMODAL MASTER CURVE ANALYSIS

P. Nevasmaa, A. Laukkanen, T. Planman and K. Wallin
VTT Industrial Systems, P.O. Box 1704, FI-02044 VTT, Finland

ABSTRACT

The basic Master Curve (MC) method for analysis of brittle fracture test results is intended only for macroscopically homogeneous ferritic steel. In reality, steels and welds often contain inhomogeneities that distort the standard MC analysis. The structural integrity assessment procedure SINTAP contains a lower tail modification of the MC analysis, enabling conservative lower bound fracture toughness estimates to be determined also for inhomogeneous material. Such estimates, however, only describe the fracture toughness of the more brittle constituent. The deficiency of SINTAP, in this respect, lies in its inability to provide any information from the more ductile material. Therefore, a probabilistic description of the complete material is not possible. This paper introduces a new extension of the MC analysis for inhomogeneous material: a bimodal MC analysis method that describes the fracture toughness distribution as the combination of two separate MC distributions. This bimodal distribution model is shown to describe successfully the weld heat-affected zone (HAZ) fracture toughness data sets that generally exhibit substantial microstructural inhomogeneity. This is especially the case with multipass weldments containing local brittle zones (LBZ).

1 INTRODUCTION

The basic Master Curve (MC) method for analysis of brittle fracture test results as defined in ASTM E1921-02 is intended for macroscopically homogeneous ferritic steels only. In reality, the steels in question are seldom macroscopically fully homogeneous. The steels fracture toughness may depend on the specimen location in the sample. For example, thick plates and forgings may have very different fracture toughness at plate center and close to surface. The inhomogeneity may be deterministic or random (or a mixture of both) in nature. Deterministic inhomogeneity can be accounted for, provided that the specimen extraction histories are known and enough specimens are tested. Random inhomogeneity is much more difficult to handle.

The structural integrity assessment procedure SINTAP contains a lower tail modification of the MC analysis. This enables conservative lower bound type fracture toughness estimates also for inhomogeneous materials. The problem is that the SINTAP method, does not provide information of the tougher material. Therefore, a probabilistic description of the complete material is not possible. Here, a new comparatively simple extension of the MC is introduced for inhomogeneities governed by two separate MC distributions. The extension is shown to be well suited to describing weld heat-affected zone (HAZ) data.

2 THE MASTER CURVE METHOD

The Master Curve (MC) method incorporates descriptions for (i) cumulative failure probability distribution of brittle cleavage fracture in a macroscopically homogeneous ferritic steel, (ii) thickness adjustment of the data from different size specimens, and (iii) temperature dependence of cleavage fracture toughness. The applied equations are given in Ref. [1].

The major limitation of the standard MC analysis is that it is only applicable to homogeneous data sets. The point is highlighted for example through a fracture toughness round robin data set from a BS4360-50D steel. If the standard MC analysis is performed [1] on this data set, a clearly non-conservative description of the material is obtained. In order to handle this kind of inhomogeneity, the SINTAP analysis procedure has been developed.

3 THE SINTAP LOWER TAIL ANALYSIS PROCEDURE

The SINTAP lower tail analysis [1] contains three steps. Step 1 gives an estimate of the median value of fracture toughness. Step 2 performs a lower tail MML estimation, checking and correcting any undue influence of excessive values in the upper tail of the distribution. Step 3 performs a minimum value estimation to check and make allowance for gross inhomogeneities in the material. In Step 3, an additional safety factor is incorporated for cases where the number of tests is small. It is recommended that all three steps are employed when the number of tests to be analysed is between 3 and 9. With an increasing number of tests, Step 3 may still be employed for indicative purposes, especially when there is evidence of gross inhomogeneity in the material, e.g., for weld metal or HAZ material. In such cases, it may be judged that the characteristic value is based upon the Step 3 result, or alternatively, such a result may be used as guidance in a sensitivity analysis or used to indicate the need for more experimental data, when appropriate.

The SINTAP procedure is efficient in providing realistic lower bound type estimates even for highly inhomogeneous materials, but it is not applicable to describe the whole distribution. Thus, the method is not well suited to probabilistic analyses, where the higher toughness material may have a strong impact on the outcome of the analysis. A more descriptive analysis of an inhomogeneous data set can be performed using a combination of two different MC distributions.

4 BIMODAL MASTER CURVE

In the case when the data population of a material consists of two combined MC distributions, the total cumulative probability distribution can be expressed as a bimodal distribution of the form:

$$P_f = 1 - p_a \cdot \exp\left\{-\left(\frac{K_{JC} - K_{\min}}{K_{01} - K_{\min}}\right)^4\right\} - (1 - p_a) \cdot \exp\left\{-\left(\frac{K_{JC} - K_{\min}}{K_{02} - K_{\min}}\right)^4\right\} \qquad (1)$$

where K_{01} and K_{02} are the characteristic toughness values for the two constituents and p_a is the probability of the toughness belonging to distribution 1. In the case of multi-temperature data, the characteristic toughness (K_{01} and K_{02}) is expressed in terms of the MC transition temperature (T_{01} and T_{02}). In contrast to a standard MC analysis where only one parameter needs to be determined, the bimodal distribution contains three parameters. Thus, the fitting algorithm is somewhat more complicated than in the case of the standard MC or the SINTAP lower tail estimation. In order to be able to handle randomly censored multi-temperature data sets, the estimation must be based on the maximum likelihood procedure.

The likelihood is expressed as:

$$L = \prod_{i=1}^{n} f_{ci}^{\delta_i} \cdot S_{ci}^{1-\delta_i} \qquad (2)$$

where f_c is the probability density function, S_c is the survival function and δ is the censoring parameter.

The probability density function has the form (Eq. 3):

$$f_c = 4 \cdot p_a \cdot \frac{(K_{JC} - K_{\min})^3}{(K_{01} - K_{\min})^4} \exp\left\{-\left(\frac{K_{JC} - K_{\min}}{K_{01} - K_{\min}}\right)^4\right\} - 4 \cdot (1 - p_a) \cdot \frac{(K_{JC} - K_{\min})^3}{(K_{02} - K_{\min})^4} \cdot \exp\left\{-\left(\frac{K_{JC} - K_{\min}}{K_{02} - K_{\min}}\right)^4\right\}$$

and the survival function has the form:

$$S_c = p_a \cdot \exp\left\{-\left(\frac{K_{JC} - K_{\min}}{K_{01} - K_{\min}}\right)^4\right\} + (1 - p_a) \cdot \exp\left\{-\left(\frac{K_{JC} - K_{\min}}{K_{02} - K_{\min}}\right)^4\right\} \qquad (4)$$

The parameters are solved so as to maximise the likelihood given by Eq. 2. The numerical iterative process is simplified by taking the logarithm of the likelihood so that a summation equation is obtained (Eq. 5).

$$\ln L = \sum_{i=1}^{n} \left[\delta_i \cdot \ln(f_{ci}) + (1 - \delta_i) \cdot \ln(S_{ci})\right] \qquad (5)$$

The capability of the bimodal distribution to describe weldment data was firstly studied by considering two HAZ data sets: one with even-matching (EM) and the other with over-matching (OM) weld metal [1]. Here, the parent steel and welding parameters for these two data sets were equivalent. Comparing the bimodal MC and SINTAP assessment methods revealed [1], for both weldments the lower tail of the bimodal estimate was very close to that corresponding to the SINTAP estimate. Both methods demonstrated consistently that the overmatching weld HAZ behaves slightly more brittle than the even-matching weld HAZ. A metallurgical selection of the two data sets was performed to include only specimens with "sufficient" amount of coarse-grained HAZ close to the pre-fatigue crack tip. Analysis of these data showed [1], the selection reduced the amount of the tougher constituent in the distributions to such a degree that reliable estimation of the tougher portion was not possible. The toughness of the tougher portion was thereby fixed to K_0 = 450 MPa√m, since the choice of the value did not affect the fit of the lower toughness portion. The metallurgical selection decreased the SINTAP estimates by 5-10%. For the bimodal estimates, the portion of the more brittle constituent was seen to increase, but the toughness values themselves were unaffected by the selection. In the case of the EM and OM welds, the lower K_0 values changed from 233 to 228 MPa√m and from 208 to 211 MPa√m, respectively. These changes were only around 2%, which indicates that by using the bimodal estimation method, time-consuming and costly metallurgical selection can be omitted.

Next, HAZ data sets were analysed [1] from two welds that differed substantially in terms of the applied heat input. One was made with 3 kJ/mm, whereas the other was made with 10 kJ/mm. The analysis became more difficult due to the fact that many of the applied specimens exceeded the specimen size criterion (M = 30). This reflects in a slightly larger uncertainty in the toughness estimate of the tougher constituent. Nevertheless, the estimates of the tougher constituents were, within 10%, identical. The smaller heat input resulted in a narrow HAZ, causing p_a to be small (0.11). The greater heat input widened the HAZ (p_a = 0.3) and decreased the toughness of the brittle constituent (K_0 = 119 → 92 MPa√m, i.e., 23% reduction). The SINTAP estimates were clearly higher than the bimodal estimates. This is due to the small values of p_a, i.e., the probability of "hitting" the brittle region is small. In such case, the SINTAP estimates are partially affected by the more ductile constituent. Whenever using the SINTAP procedure, the recommendation is therefore to carry out post-test metallography on HAZ specimens in order to avoid erroneous estimates of fracture toughness.

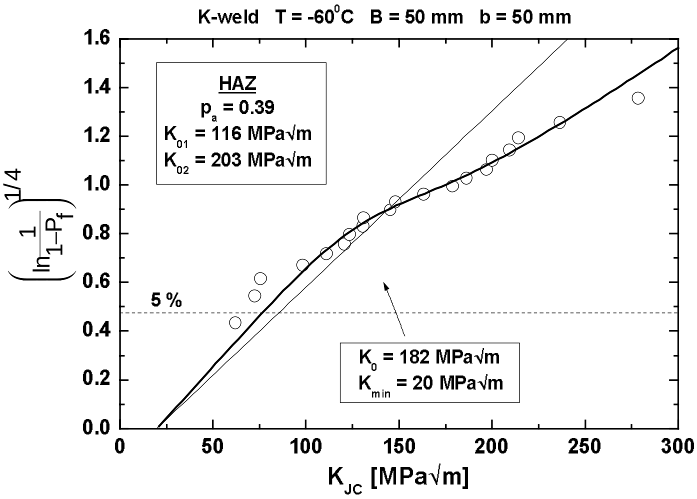

Figure 1. Bimodal MC analysis of K-groove weld HAZ results [1]. Bimodal behaviour is visible.

Two further HAZ examples are given in *Figs 1* and *2*. *Fig. 1* shows data for a K-groove weld, where the crack is located along the straight portion of HAZ [1]. This test geometry is quite typical for HAZ characterisation. The data indicate a bimodal distribution with a brittle constituent (p_a = 0.39) with a K_0 value of 116 MPa√m and a ductile constituent with a K_0 value of 203 MPa√m. *Fig. 2* displays the same material, but using an X-groove weld [1]. The X-groove forces the crack to sample the base material, the HAZ and the weld metal microstructures. In each specimen, the variation between the different constituents is quite small. This makes the specimens individually alike and they behave like if they were homogeneous material. This is confirmed in *Fig. 2* that shows no bimodal behaviour in the data. Instead, the analysis yields two very closely located K_0 values with one being dominant (93 %) and equivalent to the standard K_0 estimate. The thereby obtained K_0 value that is the result of all the three microstructural regions is seen to lie between the bimodal estimates of the K-groove weld.

As an example of the bimodal <u>multi-temperature</u> estimation, artificially embrittled A508 Cl.2 steel used in the ORNL PTSE-1 experiment was analysed [1]. Owing to the inhomogeneity of the embrittled steel, the bimodal MC expression gave two different T_0 values. The more brittle material had T_0 = +65ºC and a probability p_a = 0.34. The tougher material had T_0 = +12ºC and an occurrence probability of 0.66. The analysis showed [1] that the 5% SINTAP estimate is less conservative than the bimodal estimate. This resulted from the comparatively low probability of hitting the more brittle material (34%). In fact, if there is less than 50% brittle material, the SINTAP estimate becomes less conservative than the bimodal estimate.

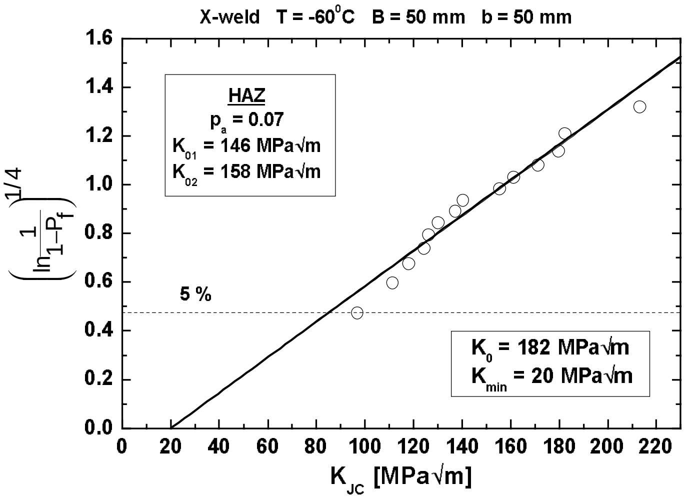

Figure 2. Bimodal MC analysis of X-groove weld HAZ results [1]. No bimodal behaviour is visible, material behaves like homogeneous.

5 DISCUSSION

The analyses of HAZ data sets [1] revealed that the SINTAP method does not yield quite as conservative estimates of the lower bound toughness as the bimodal distribution analysis. The bimodal distribution recognises both the toughness of the more brittle constituent as well as the amount of it. The bimodal distribution can thus be used to estimate the actual distribution or a hypothetical distribution consisting entirely of brittle material. The SINTAP method, in turn, gives an estimate that is mainly influenced by the amount of the more brittle constituent. However, if this amount is small, the estimate will be influenced by the toughness of the tougher constituent.

In general, the SINTAP method is intended for the analysis of small data sets, where the uncertainty related to the data set size becomes an important factor. It is awaited to provide representative lower bound estimates suitable for structural integrity analysis purposes. Thus, the SINTAP method should not be used e.g. to determine transition temperature shifts or in the cases where the average fracture toughness is of interest. For homogeneous material, the SINTAP method provides on the average a 10% lower fracture toughness estimate than the standard MC method. For inhomogeneous data sets, the difference is, of course, far greater.

The use of the bimodal MC distribution should be limited to data sets of a sufficient size to provide information about the inhomogeneity in question. The bimodal fit to the data can, as such, be very good, but a small data set may not describe the true distribution very accurately. The accuracy of the estimated parameters will depend on the data set size, occurrence probability (i.e., probability of hitting the different zones) and degree of censoring. The accuracy of the bimodal MC was investigated by performing a simple Monte Carlo simulation. It was found that the standard deviation of the more brittle material can be approximated by Eq. 6, the more ductile material by Eq. 7 and the occurrence probability of the more brittle material by Eq. 8.

$$\sigma T_{01} \approx \frac{22°C}{\sqrt{n \cdot p_a - 2}} \quad (6)$$

$$\sigma T_{02} \approx \frac{16°C}{\sqrt{r - n \cdot p_a - 2}} \quad (7)$$

$$\sigma p_a \approx \frac{0.35}{\sqrt{n \cdot p_a - 2}} \quad (8)$$

Here, n is the total number of results and r is the number of non-censored results. If in any of the equations, the denominator becomes less than 1, the bimodal estimate of the parameter in question should not be used. Eqs. 6-8 can also be used to judge the likelihood that the data represents an inhomogeneous material. A simple criteria can be expressed:

$$\left|T_{01} - T_{02}\right| > 2 \cdot \sqrt{\sigma T_{01}^2 + \sigma T_{02}^2} \quad (9)$$

If the criterion in Eq. 9 is fulfilled, the material is likely to be significantly inhomogeneous. The bimodal MC estimate for inhomogeneous material should preferably be used with larger data sets than allowed for the basic MC or SINTAP. The minimum data set size to be used with the bimodal distribution is around 12-15, but preferably greater than 20. Smaller data sets do not describe the distribution sufficiently well to allow a confident estimation of the inhomogeneity.

6 SUMMARY AND CONCLUCIONS

The standard Master Curve analysis methods are intended only for macroscopically homogeneous materials. In many cases, structural steels and their welds contain inhomogeneities that distort the standard MC analysis. For such cases, the SINTAP estimation method can be used to determine lower bound types of estimates that describe the fracture toughness of the more brittle constituent. The deficiency of the SINTAP method lies in its inability to describe also the more ductile constituent. As a remedy to this, a new bimodal MC analysis method has been proposed. The method describes the fracture toughness distribution as the combination of two separate MC distributions. The bimodal distribution model has been shown to deal very successfully with HAZ fracture toughness data sets from multipass weldments exhibiting substantial inhomogeneity.

REFERENCE

[1] Wallin K, Nevasmaa P, Laukkanen A. and Planman T.: ‘Master Curve Analysis of Inhomogeneous Materials’. *Engineering Fracture Mechanics* (in press).