RECENT ADVANCES IN MASTER CURVE TECHNOLOGY

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ABSTRACT

The Master Curve methodology is a statistical, theoretical, micromechanism based, analysis method for fracture toughness in the ductile to brittle transition region. The method, originally developed at VTT Manufacturing Technology" simultaneously account for the scatter, size effects and temperature dependence of fracture toughness. The method has been successfully applied to a very large number of different ferritic steels and it forms the basis of the ASTM testing standard for fracture toughness testing in the transition region. The Master Curve (MC) methodology has evolved from only being a brittle fracture testing and analysis procedure to a technological tool capable of addressing many more structural integrity issues like constraint and parameter transferability. Here, some recent advances of the technology are presented. The advances include eg. constraint adjustment, description of warm pre-stress effects, analysis of inhomogenous materials and assessment of real three-dimensional flaws.

1 INTRODUCTION

The master curve method is a statistical, theoretical, micromechanism based, analysis method for fracture toughness in the ductile to brittle transition region. The method, originally developed at VTT Manufacturing Technology" simultaneously account for the scatter, size effects and temperature dependence of fracture toughness, as schematically presented in fig. 1 (Wallin [1]).

The method has been successfully applied to a very large number of different ferritic steels and it forms the basis of the ASTM testing standard for fracture toughness testing in the transition region (ASTM E1921-02). Worldwide, there is ongoing comprehensive validation and development work to include the Master Curve method, as a new reference fracture toughness concept, into different structural integrity assessment codes, like ASME.

The MC enables a complete characterization of a material's brittle fracture toughness based on only a few small-size specimens. The MC method has been shown to be applicable for practically all steels with a body-centered cubic lattice structure, generally identified as ferritic steels.

The method enables the use of small specimens for quantitative fracture toughness estimation, thus reducing testing costs and enabling surveillance size specimens to be used for a direct measurement of fracture toughness. It also improves the quality of lower bound fracture toughness estimates, thus reducing the need for overly conservative safety factors. The applicability of the method is not restricted to nuclear applications. Its biggest impact is foreseen to be on fracture toughness determination for conventional structures, where testing costs and material use are presently inhibiting the use of fracture mechanics in design.

Recently, the MC methodology has evolved from only being a brittle fracture testing and analysis procedure to a technological tool capable of addressing many more structural integrity issues like constraint and parameter transferability.

2 RECENT ADVANCES

Recent advances in connection with the Master Curve have beeen achieved in the description of constraint effects, describing the warm pres-stress effect, the analysis of inhomogeneous materials and the assessment of real three-dimensional flaws.

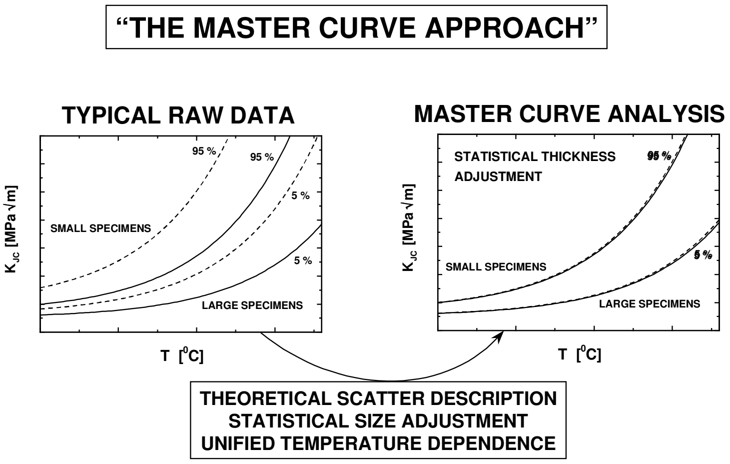

Figure 1: Principle of the Master Curve approach (Wallin [1]).

2.1 Constraint adjustment (Wallin [2])

A considerable number of materials and specimen test geometries have been analysed to examine the relation between the Master Curve T_0 transition temperature and the geometry related constraint expressed by the T-stress. In all cases, the relation between T_0 and T-stress could be satisfactorily approximated by a straight line relationship. The straight line approximation appears to be valid also for positive T-stress values of the magnitude encountered in the study (T-stress < 300 MPa). The functional form of the constraint dependence containing also the materials yield strength is

$$\Delta T_0 = A \cdot \frac{T - stress}{\sigma_{YT}} \qquad (1)$$

An approximate average description of the sensitivity is represented by $A = \sigma_{YT}/12$ MPa/ºC (Fig.2).

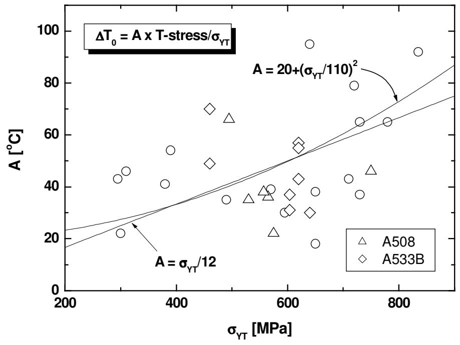

Figure 2: Relation between constraint sensitivity (A) and yield strength (σ_{YT}).

2.2 Warm pre-stress adjustment (Wallin [3])

The WPS effect describes the effect of a prior loading on the subsequent effective fracture toughness. When a crack is loaded to some crack driving parameter (K, J or CTOD), that is lower than the fracture toughness at the temperature in question, the effect will be an effective increase in fracture toughness if the specimen is re-loaded at a lower temperature at which the prior loading exceeds the fracture toughness (Fig. 2). Experimental investigations have focussed on LCF (Load Cool Fracture), LUCF (Load Unload Cool Fracture) and LPUCF (Load Partial Unload Cool Fracture). The existence of the WPS effect is unquestionable if the result is not affected by time dependent processes. So far, investigations have compared the WPS affected result, with the mean "baseline" fracture toughness value. This is appropriate for determination of the mean behavior, but makes interpretation and use with respect to scatter difficult. In structural integrity assessment, where a lower bound type fracture toughness estimate (like the 5 % or 1 % MC) is used, it is imperative to know that also the WPS affected value corresponds to an equivalent lower bound. Therefore, it is important to know how WPS affects the apparent fracture toughness scatter.

A comprehensive study of a large WPS data base was performed. The data base, consisting of 751 WPS results, covered a wide variety of materials and WPS transients. In all cases studied, the existence of the WPS effect could be verified. The data indicates that yield stress changes during the WPS transient, has a negligible effect on the failure fracture toughness. A new simple WPS correction, capable of handling all transients with equal confidence, was developed and verified.

$$\begin{aligned} & K_f = 0.15 \cdot K_{IC} + \sqrt{K_{IC} \cdot \left(K_{WPS} - K_2\right)} + K_2 \\ & \mathit{if} \quad K_2 \geq K_{WPS} - K_{IC} \Rightarrow K_2 = K_{WPS} \\ & \mathit{if} \quad K_f \leq K_{IC} \Rightarrow K_f = K_{IC} \end{aligned} \tag{2}$$

The correction contains a slight built-in conservatism and is applicable for both best estimates and, combined with the Master Curve, lower bound type estimates to be used in structural integrity assessments. The simple correction was compared to the correction proposed by Chell. The accuracy of the two corrections was shown to be similar, but the simple correction, requires less input information and is considerably easier to use.

The new simple WPS correction is thus capable of handling any WPS transient with satisfactory accuracy and, combined with the Master Curve, is also capable of handling the effect of WPS on the apparent fracture toughness scatter, enabling the estimation of desired lower bound values.

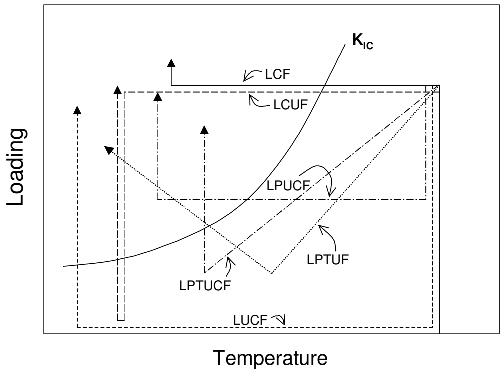

Figure 2: Definition of different WPS transients.

2.3 Inhomogenous materials (Wallin [4])

The major limitation of the standard MC analysis is that it is only applicable to homogeneous data sets. In order to handle inhomogeneity, the SINTAP analysis procedure has been developed. The SINTAP procedure is very 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 for 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 by using a combination of two different MC distributions (Bimodal MC). The method is especially applicable for heat affected zone fracture toughness data. An other possible procedure for the analysis of data sets consisting of mixed data is based on a maximum likelihood estimate for random inhomogeneity. The method is especially applicable for data sets including several different materials.

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

$$P_f = 1 - p_a \cdot \exp\left\{-\left(\frac{K_{JC} - K_{\min}}{K_{01} - K_{\min}}\right)^4\right\} - (1 - p_a) \cdot \exp\left\{-\left(\frac{K_{JC} - K_{\min}}{K_{02} - K_{\min}}\right)^4\right\} \tag{2}$$

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. This means that the fitting algorithm is somewhat more complicated than in the case of the standard MC or the SINTAP lower tail estimate. In order to be able to handle randomly censored multi-temperature data sets, the estimation must be based on the maximum likelihood procedure.

The procedure for the random inhomogeneity analysis is somewhat more complicated and is not presented here. An example of the bimodal MC analysis is presented in fig. 3, where it is compared with the SINTAP step 2 analysis.

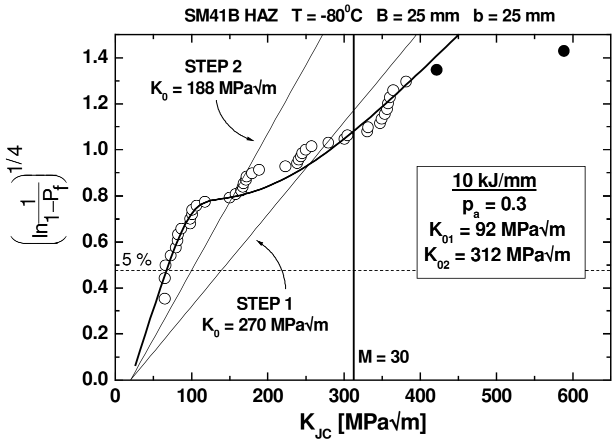

Figure 3: Bimodal MC analysis of high heat input HAZ data, compared to SINTAP analysis result.

2.4 Assessment of real three-dimensional flaws (Wallin [5])

Normally, the Master Curve parameters are determined using test specimens with "straight" crack fronts and comparatively uniform stress state along the crack front. This enables the use of a single K_I value and single constraint value to describe the whole specimen. For a real crack in a structure, this is usually not the case. Normally, both K_I and constraint varies along the crack front and in the case of a thermal shock, even the temperature will vary along the crack front. Generally real cracks are simplified in the form of ellipses in order to aid the analysis. An example of an elliptic surface crack is shown in fig. 2.

The standard Master Curve cumulative failure probability expression is of the form:

$$P_f = 1 - \exp\left\{ \frac{B}{B_0} \cdot \left(\frac{K_I - K_{\min}}{K_0 - K_{\min}} \right)^4 \right\} \tag{3}$$

where B is the specimen thickness, B_0 is the normalisation thickness 25 mm, K_{min} is the minimum fracture toughness 20 MPa√m, K_I is the crack driving force and K_0 is the fracture toughness corresponding to 63.2 % failure probability.

For a real three dimensional crack, both K_I and K_0 may vary as a function of location (Φ) along the crack front. This leads to the need of a more general expression for the cumulative failure probability (Eq. 2). The expression gives the cumulative failure probability, but it is not suited for a simple visualisation of the result.

$$P_f = 1 - \exp\left\{ \int_0^s \left(\frac{K_{I\Phi} - K_{\min}}{K_{0\Phi} - K_{\min}} \right)^4 \cdot \frac{ds}{B_0} \right\} \tag{4}$$

A visualisation, that is in line with present structural integrity practice, can be achieved by defining an effective stress intensity factor K_{Ieff} corresponding to a specific reference temperature. The reference temperature can e.g. be chosen as the minimum temperature along the crack front. The procedure is to determine an effective driving force, which would give the same failure probability as Eq. 2, in the context of a standard Master Curve presentation. This means essentially a combination of Eqs. 1 and 2. The result is presented in Eq. 3.

$$K_{IeffTref} = \left\{ \int_0^s \left(\frac{K_{I\Phi} - K_{\min}}{K_{0\Phi} - K_{\min}} \right)^4 \cdot \frac{ds}{B_0} \right\}^{1/4} \cdot \left(K_{0Tref} - K_{\min} \right) + K_{\min} \tag{5}$$

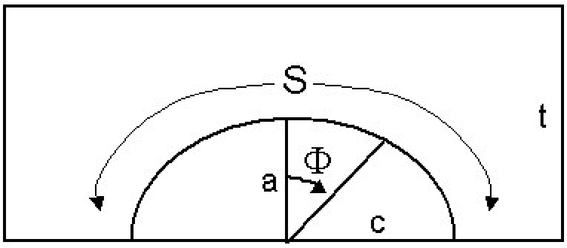

Figure 2: Definition of dimensions of elliptic surface crack.

3 SUMMARY AND CONCLUSIONS

The Master Curve methodology is a statistical, theoretical, micromechanism based, analysis method for fracture toughness in the ductile to brittle transition region. The method, originally developed at VTT Manufacturing Technology" simultaneously account for the scatter, size effects and temperature dependence of fracture toughness. The method has been successfully applied to a very large number of different ferritic steels and it forms the basis of the ASTM testing standard for fracture toughness testing in the transition region. The Master Curve (MC) methodology has evolved from only being a brittle fracture testing and analysis procedure to a technological tool capable of addressing many more structural integrity issues like constraint and parameter transferability. Here, some recent advances of the technology have been presented. The Master Curve now include eg. possibility for constraint adjustment, a description of warm pre-stress effects, quantitavive analysis of inhomogenous materials and enables assessment of real three-dimensional flaws.

4 ACKNOWLEDGEMENTS

This work is a part of the Integrity and Life Time of Reactor Circuits project (INTELI) belonging to the Safety of Nuclear Power Plants - Finnish national research programme 2003-2006 (SAFIR), financed by the Ministry of Trade and Industry, the Technical Research Centre of Finland (VTT) and the Radiation and Nuclear Safety Authority (STUK).

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