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Implementation of the Master Curve method in ProSACC

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SSM perspective

Background

Cleavage fracture toughness data display normally large amount of statistical scatter in the transition region. The cleavage toughness data in this region is specimen size-dependent, and should be treated statistically rather than deterministically. The Master Curve (MC) methodology is a procedure for mechanical testing and statistical analysis of fracture toughness of ferritic steels in the transition region.

The methodology accounts for temperature and size dependence of fracture toughness. Using the Master Curve methodology for evaluation of the fracture toughness in the transition region relaxes some of the over-conservatism that has been observed in using the ASME-KIC curve.

The authority has in an earlier project sponsored research to evaluate the technical basis for the Master Curve (MC) concept, see SKI Research Report 2005:55. In the current report, the implementation of the MC concept into the program code ProSACC is described.

Objectives

The principal objective of the project has been to describe the implementation of the MC concept into the code ProSACC.

Results

The main options of the Master Curve methodology are implemented in the ProSACC code.

The code gives fracture toughness values at the given temperature based on input data on T0 from fracture toughness testing, or Charpy impact test results (T28J or T41J) or KIC value from fracture toughness testing on the actual material.

There is also a possibility in the code to make crack-size correction on the evaluated fracture toughness.

Application of different Master Curve options in code is illustrated in three examples given in Appendices of the report.

Need for further research

The results of this project can be used for safety assessments of cracks in the core region of reactor pressure vessels by using the code ProSACC. More research is possibly needed for the further investigation of how the Master Curve Concept can be developed for including constraint effects.

Project information

Contact person SSM: Björn Brickstad
Reference: SSM 2009/770.

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Swedish Radiation Safety Authority

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This report concerns a study which has been conducted for the Swedish Radiation Safety Authority, SSM. The conclusions and view-points presented in the report are those of the author/authors and do not necessarily coincide with those of the SSM.

Table of content Page

SUMMARY

In this work, the main options of the Master Curve methodology are implemented in the ProSACC program. Different options in evaluating Master Curve fracture toughness from standard fracture toughness testing data or impact testing data are considered. In addition, the possibility to make size-correction due to crack size is considered in the program. Finally, in order to illustrate the application of the Master Curve methodology in evaluation of fracture toughness in structural integrity assessments using ProSACC, three examples are given in the Appendices of this report.

1 Introduction

Cleavage fracture toughness data display normally large amount of statistical scatter in the transition region. The cleavage toughness data in this region is specimen size-dependent, and should be treated statistically rather than deterministically. Master Curve methodology is a procedure for mechanical testing and statistical analysis of fracture toughness of ferritic steels in the transition region. The methodology accounts for temperature and size dependence of fracture toughness. Using the Master Curve methodology for evaluation of the fracture toughness in the transition region releases the over-conservatism that has been observed in using the ASME-K_{IC} curve. The ASTM E1921-03 standard describes the determination of the reference temperature T_0, which characterizes the fracture toughness of ferritic steels at onset of cleavage cracking at elastic or elastic-plastic instability. By definition, T_0 is a temperature at which the median of the K_{JC} distribution from 1T size specimens is 100 MPa√m. Based on the determined Master Curve T_0, fracture toughness curves of different fracture probabilities (3, 5, 50 and 95% probability) can be developed. One main advantage of using the Master Curve methodology is possibility to use small Charpy-size specimens to determine fracture toughness. Detailed description of the Master Curve methodology is given by Sattari-Far and Wallin [2005]. A short description of the methodology is given in the following section of this report.

ProSACC is a suitable program in using for structural integrity assessments of components containing crack like defects and for defect tolerance analysis, Dillström et al [2004a, 2004b]. The program gives possibilities to conduct assessments based on deterministic or probabilistic grounds. The method utilized in ProSACC is based on the R6-method developed at Nuclear Electric plc, Milne et al [1988]. The basic assumption in this method is that fracture in a cracked body can be described by two parameters K_r and L_r. The parameter K_r is the ratio between the stress intensity factor and the fracture toughness of the material. The parameter L_r is the ratio between applied load and the plastic limit load of the structure. The ProSACC assessment results are therefore highly dependent on the applied fracture toughness value in the assessment.

In this work, the main options of the Master Curve methodology are implemented in the ProSACC program. Different options in evaluating fracture toughness from standard fracture toughness testing and impact testing are considered. In addition, the possibility to make size-correction due to crack size is considered in the program. Finally, in order to illustrate the application of the Master Curve methodology in evaluation of fracture toughness in structural integrity assessments using ProSACC, three examples are given in the Appendices of this report.

2 Description of the Master Curve method

2.1 GENERAL ASPECTS

Fracture mechanics, based on a continuum mechanics, gives means in understanding of fracture behaviour in cracked bodies. It is commonly assumed that there exists a single fracture toughness value controlling the materials fracture. If the crack driving force in the body is less than this value, the crack will not propagate and if it exceeds this value the crack will propagate.

The micromechanism of cleavage fracture exhibits a strong sensitivity to the stress field at the crack tip. Moreover, the highly localized phenomenon of cleavage fracture also demonstrates high sensitivity to the random inhomogeneities in the material along the crack front. Consequently, cleavage fracture toughness values which meet the specified size requirements nevertheless display large amount of statistical scatter, especially for temperatures corresponding to the transition region. Because of this substantial scatter, cleavage toughness data should be treated statistically rather than deterministically. It means that a given steel does not have a single value of toughness at a particular temperature in the transition region; rather, the material has a toughness distribution. Testing of numerous specimens to obtain a statistical distribution of the fracture toughness can be expensive and time-consuming. In addition, there has been an interest to utilize small fracture specimens, e.g. of Charpy size, to obtain fracture toughness data when severe limitations exist on material availability, for instance when considering irradiation embrittlement for ferritic materials. To reduce these problems, a methodology has been developed that greatly simplifies the process of determination of fracture toughness in the transition region. The ASTM E 1921-03 standard [2003] describes the procedure for the mechanical testing and statistical data analysis of ferritic steels in the transition region. This ASTM standard accounts for temperature dependence of toughness through a Fracture Toughness Master Curve approach developed by Wallin [1991]. Wallin observed that a wide range of ferritic steels have a characteristic fracture toughness-temperature curve, and the only difference between different steels was the absolute position of the curve with respect to temperature. The temperature dependence of the fracture toughness can be determined by performing a certain amount of fracture toughness tests at a given temperature.

The statistical size effect, due to the weakest link nature of cleavage fracture initiation, is active also for valid K_{IC} results, provided they are above the lower shelf. A good example of this is given by the HSST 02 plate data used originally to develop the ASME K_{IC} reference curve shown in Fig. 2.1, [Marston, 1978]. The data, originally known as the "million dollar curve", constituted the first large fracture toughness data set generated for a single material. Normally, only the valid K_{IC} results are reported, but for clarity, here also the invalid results are included. It is evident that there is a difference between the smaller 1T & 2T specimens and the larger 4T & 6T specimens. The evaluation of these data will be fully in line with the theoretical statistical size effect in the Master Curve methodology, as shown in Fig. 2.2.

Another example showing the decrease in K_{IC} with increasing specimen size (thickness B) has been presented by MPA, shown in Fig. 2.3, [Issler, 1979]. Even though the data are limited in number, it clearly indicates decreasing fracture toughness with increasing specimen size, for all valid K_{IC} values. Also in this case, the size effect is in line with the theoretical prediction of the Master Curve. Numerous similar data sets can easily be found in the open literature.

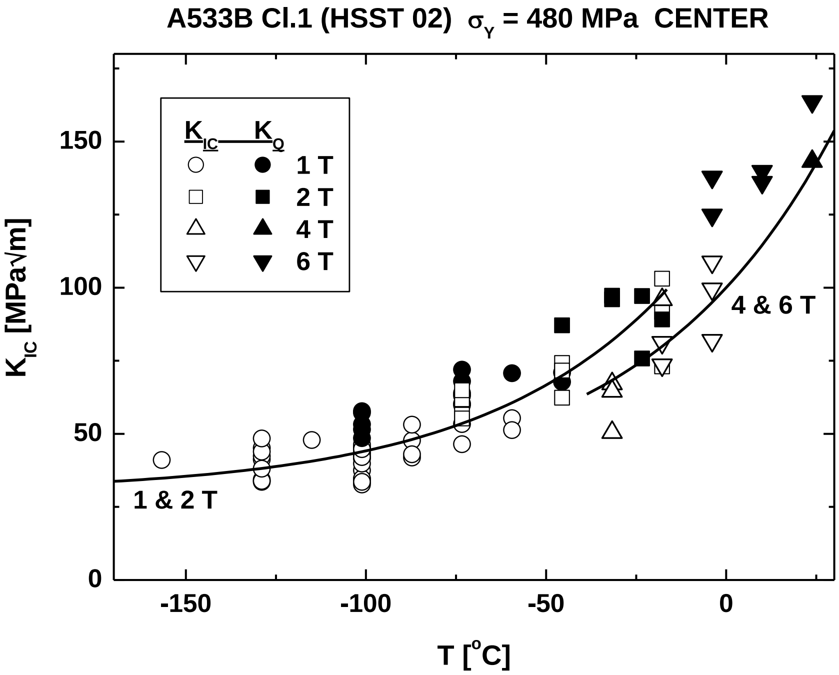


Fig. 2.1. Valid brittle fracture K_{IC} data for the HSST 02 plate indicating decreasing fracture toughness with increasing specimen size, (Marston, [1978]).

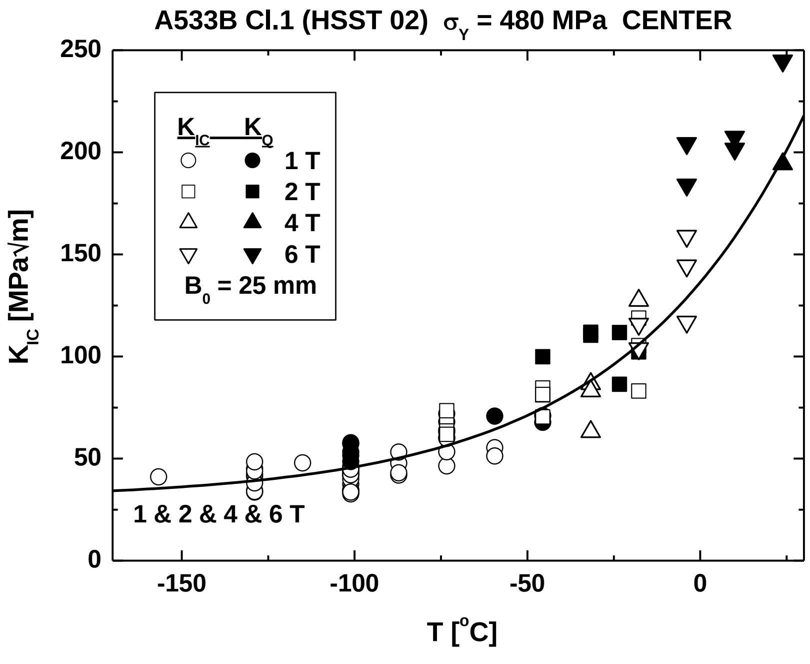


Fig. 2.2: Master Curve evaluation of brittle fracture K_{IC} data for the HSST 02 plate.

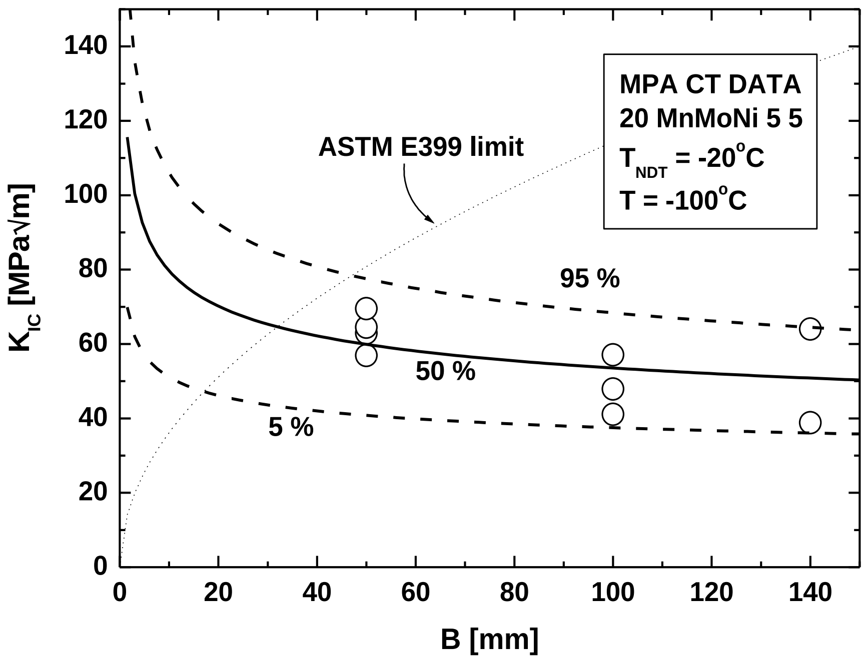


Fig. 2.3: MPA brittle fracture K_{IC} data, for KS13, showing size effect in accordance with the Master Curve, (Issler, [1979]).

2.2 MASTER CURVES ACCORDING TO ASTM E1921-03 STANDARD

The ASTM E1921-03 standard describes the determination of a reference temperature, T_0 in °C, which characterizes the fracture toughness of ferritic steels that experience onset of cleavage cracking at elastic, or elastic-plastic K_{Jc} instability, or both. By definition, T_0 is a temperature at which the median (50% fracture probability) of the K_{Jc} distribution from 1T size specimens will be equal to 100 MPa√m. Static elastic-plastic fracture tests are performed on standard SEN(B) or CT specimens having deep notches (a/W= 0.5) to measure the J-integral values at cleavage fracture (denoted J_c). The test temperature (T) and configuration of all specimens must be identified. The test temperature should be selected in the lower part of the ductile-to-brittle region as close as possible to the eventual T_0. The standard requires a minimum of six replicate tests which meet the crack front straightness tolerances, the limits on ductile tearing prior to cleavage, the size/deformation limits, etc. It is also possible to use miniature specimen sizes in the fracture toughness test. For example, using test specimens of section 5x5 mm^2 needs 12 validated tests. The J-integral values at fracture are converted to their equivalent units of stress intensity factor using:

$$K_{Jc} = \sqrt{\frac{EJ_c}{1-\nu^2}} \qquad \mathrm{MPa}\sqrt{\mathrm{m}}\,, \tag{1}$$

where E denotes the elastic modulus and ν the Poisson's ratio of the material. The maximum K_{Jc} capacity of a specimen is restricted to:

$$K_{Jc(\mathrm{limit})} = \sqrt{\frac{Eb_0\sigma_Y}{M(1-\nu^2)}}\,, \tag{2}$$

where σ_Y is the material yield strength at the test temperature and b_0 the specimen remaining ligament. The standard sets M = 30 in order to assure that the small scale yielding (SSY) condition prevails in the test specimen. K_{Jc} data that exceed this requirement may be used in a data censoring procedure described in the standard, including additional restrictions. For test program conducted on other than 1T specimens, the measured toughness data should be size-corrected to their 1T equivalent according to:

$$K_{Jc(1T)} = 20 + \left[K_{Jc(x)} - 20\right]\left(\frac{B_{\mathrm{x}}}{B_{1T}}\right)^{1/4}, \tag{3}$$

where $B_{1\mathrm{T}}$ is the 1T specimen size (25 mm) and B_{x} the corresponding dimension of the test specimen. In Eqn. (3), 20 MPa√m represents the minimum (threshold) fracture toughness adopted for ferritic steels addressed by the standard.

The ASTM E1921-03 standard adopts a three-parameter Weibull model to define the relationship between K_{Jc} and the cumulative failure probability, P_f. The term P_f is the probability for failure at or before K_{Jc} for an arbitrarily chosen specimen taken from a large population of specimens. By specifying two of the three Weibull parameters, the failure probability has the form:

$$P_f = 1 - \exp\left(-\left[\frac{K_{Jc} - K_{\min}}{K_0 - K_{\min}}\right]^4\right). \tag{4}$$

Here, the Weibull distribution shape has been assigned a value of 4 derived from theoretical arguments. For ferritic steels with yield strengths ranging from 275 to 825 MPa, the cumulative probability distribution of the fracture toughness is independent of specimen size and test temperature, when K_{min} is set as 20 MPa√m. The scale parameter K_0 is the data-fitting parameter. K_0 corresponds to 63% cumulative probability. When using the maximum likelihood statistical method of data fitting, K_{Jc} and K_0 are equal, and p_f is 0.632. The following equation can be used for a sample that consists of six or more valid K_{Jc} values in order to evaluated K_0.

$$K_0 = \left[\sum_{i=1}^{N} \frac{(K_{Jc(\mathrm{i})} - 20)^4}{N}\right]^{1/4} + 20, \tag{5}$$

where N denotes the number of valid tests (six minimum). Note that K_0 can also be evaluated using both valid and censored test data. The procedure for this is given in the ASTM E1921-03 standard.

The estimated median (50% probability) K_{Jc} value, assuming p_f = 0.50 in Eqn. (4), of the population at the tested temperature can be obtained from K_0 as expressed in Eqn. (6):

$$K_{Jc(\mathrm{med})} = 0.9124(K_0 - 20) + 20. \tag{6}$$

The Master Curve is defined as the median (50% probability) toughness for the 1T (25 mm thick) specimen over the transition range for the material. Based on fitting to test results, the shape of the Master Curve for the 1T specimen is described for 50% fracture probability by Eqn. (7):

$$K_{Jc(50\%)} = 30 + 70\exp\left[0.019(T\text{-}T_0)\right]. \tag{7}$$

The lower-bound 3% and 5% probability curves and the upper-bound 95% probability curve can also be set up. These three curves are given by the following expressions:

$$K_{Jc(3\%)} = 24.6 + 32.2\exp\left[0.019(T\text{-}T_0)\right]. \quad (8)$$

$$K_{Jc(5\%)} = 25.4 + 37.8\exp\left[0.019(T\text{-}T_0)\right]. \quad (9)$$

$$K_{Jc(95\%)} = 34.6 + 102.2\exp\left[0.019(T\text{-}T_0)\right]. \quad (10)$$

Where, K_{Jc} is in MPa√m and T and T_0 in ^{o}C.

Finally, the reference temperature T_0 (^{o}C), for which K_{Jc} is 100 MPa√m, is obtained from the following expression:

$$T_0 = T - \frac{1}{0.019}\ln\left[\frac{K_{Jc(50\%)} - 30}{70}\right]. \quad (11)$$

For crack configurations that have a crack sizes (crack-front length) other than 1T (25 mm) specimens, the Master Curve toughness should be size-corrected to its 1T equivalent according to:

$$K_{JC}^{cfl} = 20 + \left[K_{JC}^{1T} - 20\right]\left(\frac{25}{cfl}\right)^{1/4} \quad (12)$$

Where K_{JC}^{cfl} is the size-corrected fracture toughness related to the actual crack-front-length (*cfl*), and K_{JC}^{1T} is the evaluated standard fracture toughness from 1T (25 mm) specimens. The upper limit for crack-front-length correction is 100 mm, according to Sattari-Far and Wallin [2005].

2.3 CORRELATION BETWEEN MASTER CURVE T_0 AND CHARPY IMPACT TEST RESULTS

A consistent use of the Master Curve method for the assessment of nuclear reactor pressure vessels, require that an estimate of the Master Curve transition temperature T_0 is obtained from the Charpy impact test information (usually obtained from the surveillance program test). This issue is complicated by the fact that the quality and quantity of Charpy test data varies from case to case. Sometimes the whole Charpy transition curve may be available, while in the other cases only part of the transition curve, or even only a single temperature, is included. There must be a consistent method of applying such different quality data to estimate T_0.

Two different Charpy-V notch (CVN) correlations have been published, specifically developed for the Master Curve T_0, Wallin [1989] and Sokolov and Nanstad [1999]. The first one is a correlation between T_0 and the 28J CVN transition temperature that is also used in the SINTAP structural integrity assessment procedure and the standard BS 7910. This correlation is presented in Fig. 2.4. The second correlation was developed by ORNL between T_0 and the 41J CVN transition temperature, which is the transition temperature most commonly used in nuclear surveillance work. This correlation is presented in Fig. 2.5.

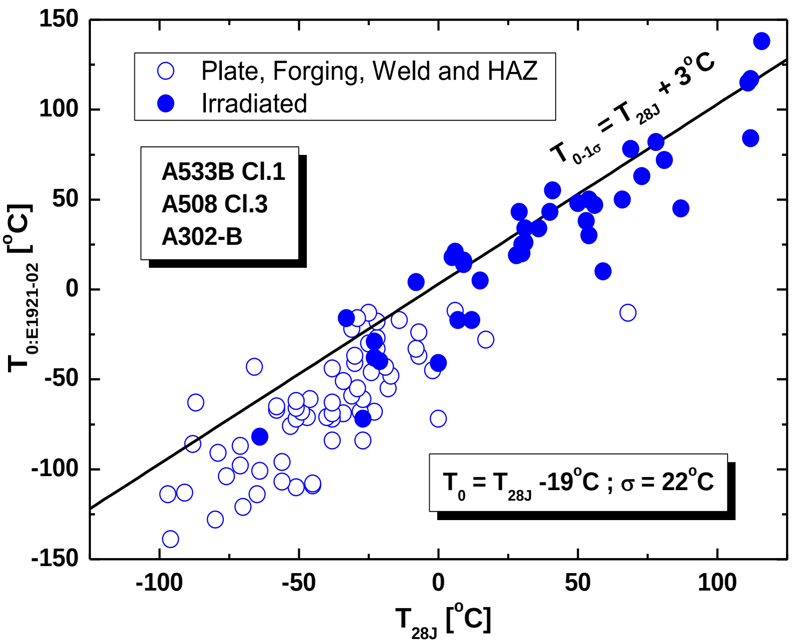


Fig. 2.4: Correlation for T_{28J} transition temperature including only western nuclear pressure vessel materials with valid T_0 values.

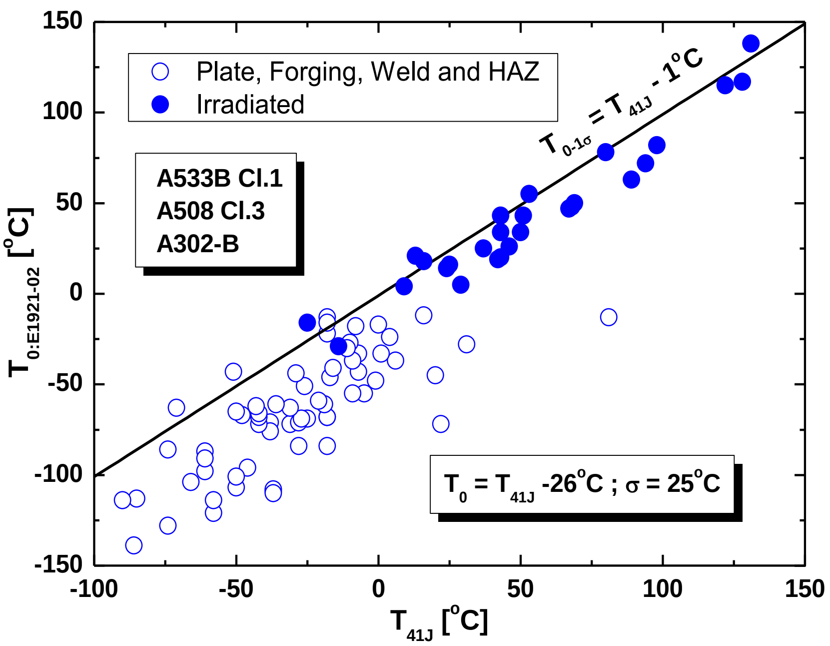


Fig. 2.5: Correlation for T_{41J} transition temperature, where only western nuclear pressure vessel materials with valid T_0 values are included.

Based on the relevant evaluated data from these two investigations, correlations between T_0 and T_{28J} and T_{41J} are presented in Eqns. (13) and (14), recommended in using for western nuclear grade pressure vessel steels and their welds:

$$T_0 = T_{28J} + 3 \ [^{\circ}\mathrm{C}] \tag{13}$$

$$T_0 = T_{41J} - 1 \ [^{\circ}\mathrm{C}] \tag{14}$$

The higher T_0 value from these two equations may be used as the representative T_0 of the material in estimation of the cleavage fracture toughness of the material from the Master Curve.

2.4 VALIDATION WINDOW OF MASTER CURVES

The reference temperature T_0 should be relatively independent of the test temperature that has been selected. Hence, data that are distributed over a restricted temperature range, namely $T_0 \pm 50\ ^{\circ}\mathrm{C}$, can be used to determine T_0. This temperature range together with the specimen size requirement, Eqn. (2), provides a validity window for application of the Master Curve methodology, as shown in Fig. 2.6.

Note that the standard Master Curves describe the cleavage fracture toughness of the material under high constraint conditions for which the single parameter characterization of the material toughness (K_{Jc}) holds. The ASTM E1921 standard does not require testing of 1T size specimens. It is also allowed to use Charpy size fracture specimens (*W*= *B*= 10 mm, *a/W*= 0.5) and convert the results to 1T equivalent values using Eqn. (3). This is a major advantage of the Master Curve methodology, having in mind the severe limitations which exist on material availability in nuclear irradiation embrittlement studies. The ASTM procedure includes limits relative to specimen size and K_{Jc}-values through Eqn. (2). Indeed, the *M*= 30 value has been selected largely on the basis of experimental data sets to ensure the existence of the SSY condition at fracture of the replicate test specimens.

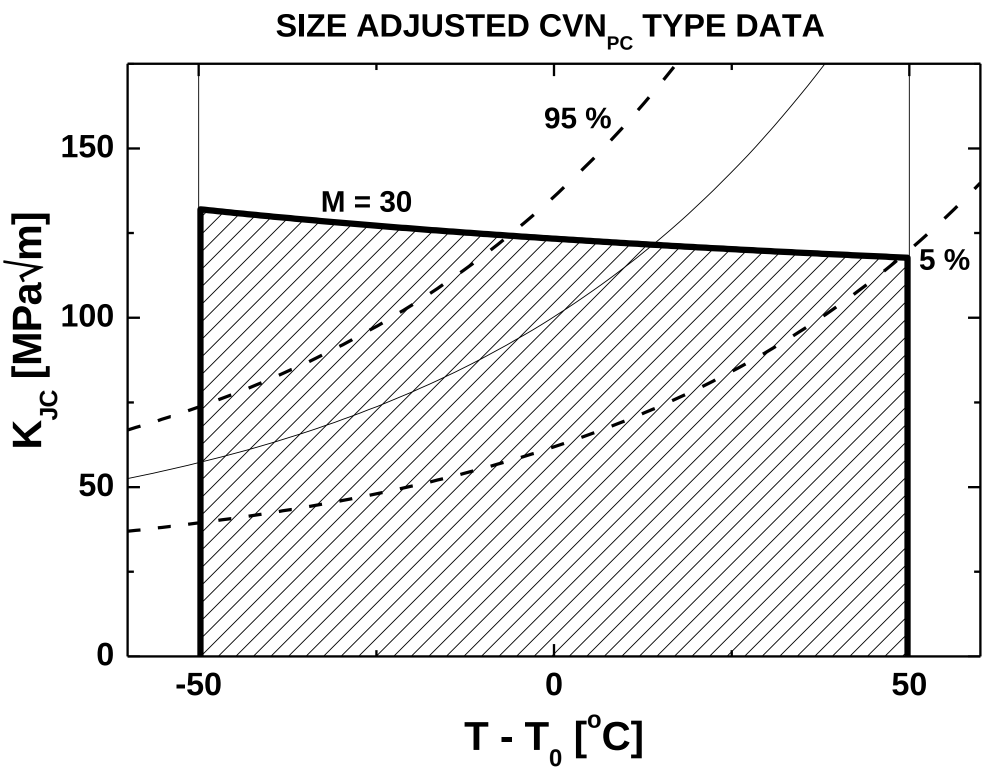


Fig. 2.6: Validation window in application of the Master Curves for the ferritic materials.

Some of the main aspects of the Master Curve method in application for integrity assessments of reactor pressure vessels are as below:

1. The Master Curve assumptions on data scatter, size effect, minimum fracture toughness and temperature dependence are valid.

2. Testing should include several test temperatures, in order to minimise any effects from a possible small deviation from the Master Curve temperature dependence.

3. Determination of T_0 should be based on test results in the temperature range of:

$$-50°C \leq T - T_0 \leq +50°C.$$

4. If only approximate information regarding the fracture toughness is required, the Master Curve can be extrapolated outside the range -50°C ≤ $T - T_0$ ≤ +50°C. If an accurate description of the fracture toughness outside this temperature range is required, tests should preferably be performed at the specific temperature of interest.

3 Implementation of the Master Curve in ProSACC

Different options within the Master Curve methodology are implemented in ProSACC in order to give possibilities for the user to conduct more comprehensive integrity assessment. It gives the user the possibilities to use 3%, 5% and 50% fracture probability in the analyses, based on Eqns. (7) to (9). It also gives the possibility to evaluate the fracture toughness K_{JC} from Charpy data (T_{28J} or T_{41J}), based on Eqns. (13) and (14). In addition, the user has the option to make size-correction for the fracture toughness, based on the actual crack configuration, Eqn. (12). The procedure to use these options in ProSACC is briefly described below.

3.1 DETERMINATION OF MASTER CURVE K_{JC} FOR 1T-THICKNESS

The Material box of the new ProSACC (upgraded with the Master Curve methodology) is shown in Fig. 3.1. If the user selects “Master Curve” for fracture toughness, a dialog box with the following four options will be opened to fill the input data in evaluation of the Master Curve toughness, as shown in Fig. 3.2:

i) There is a valid T_0 value from fracture toughness testing on the actual material.

ii) There is valid value on T_{28J} from Charpy impact testing on the actual material.

iii) There is valid value on T_{41J} from Charpy impact testing on the actual material.

iv) There is a valid K_{IC} value from fracture toughness testing on the actual material.

The user should give the relevant value to the parameter of his option (T_0 or T_{28J} or T_{41J} or K_{IC}) and the actual temperature for which the program will compute K_{JC}. In addition, he should select which fracture probability (3% or 5% or 50%) is intended for the ProSACC analysis. There is also the option to adjust the K_{JC} value for the crack front length. This option is described in the next section. The program will compute the relevant fracture toughness K_{JC}, and the results will come in the following box, as shown in Fig. 3.2, which gives the fracture toughness for 3% fracture probability when using T_0 as input data. The corresponding results when T_{28J} is used as input data and fracture toughness for 5% probability is desired are shown in Fig. 3.3. The program gives also the possibility to have a plot on the results, by selecting the “Graph” bottom. The results are shown in Fig. 3.4, where the user gets information on different Master curves, the range of application window for the actual material, the input or evaluated T_0 value, and the fracture toughness for the actual temperature (T_{act}). If the given T_{act} is outside the application window, the fracture toughness assessment based on Master Curve is not valid, and the user gets a warning on that.

To edit an already calculated K_{JC} value shown on the Material tab, the user should select the yellow coloured K_{JC} result, and the Master Curve input window will be opened for editing.

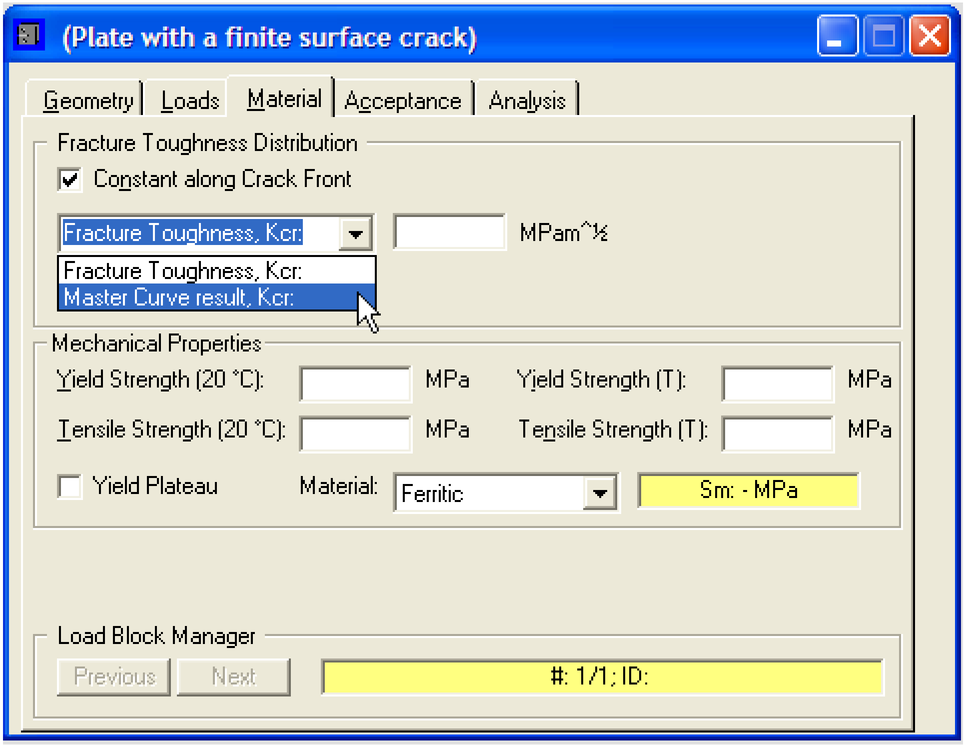


Fig. 3.1: Material box in ProSACC for input data related to fracture toughness.

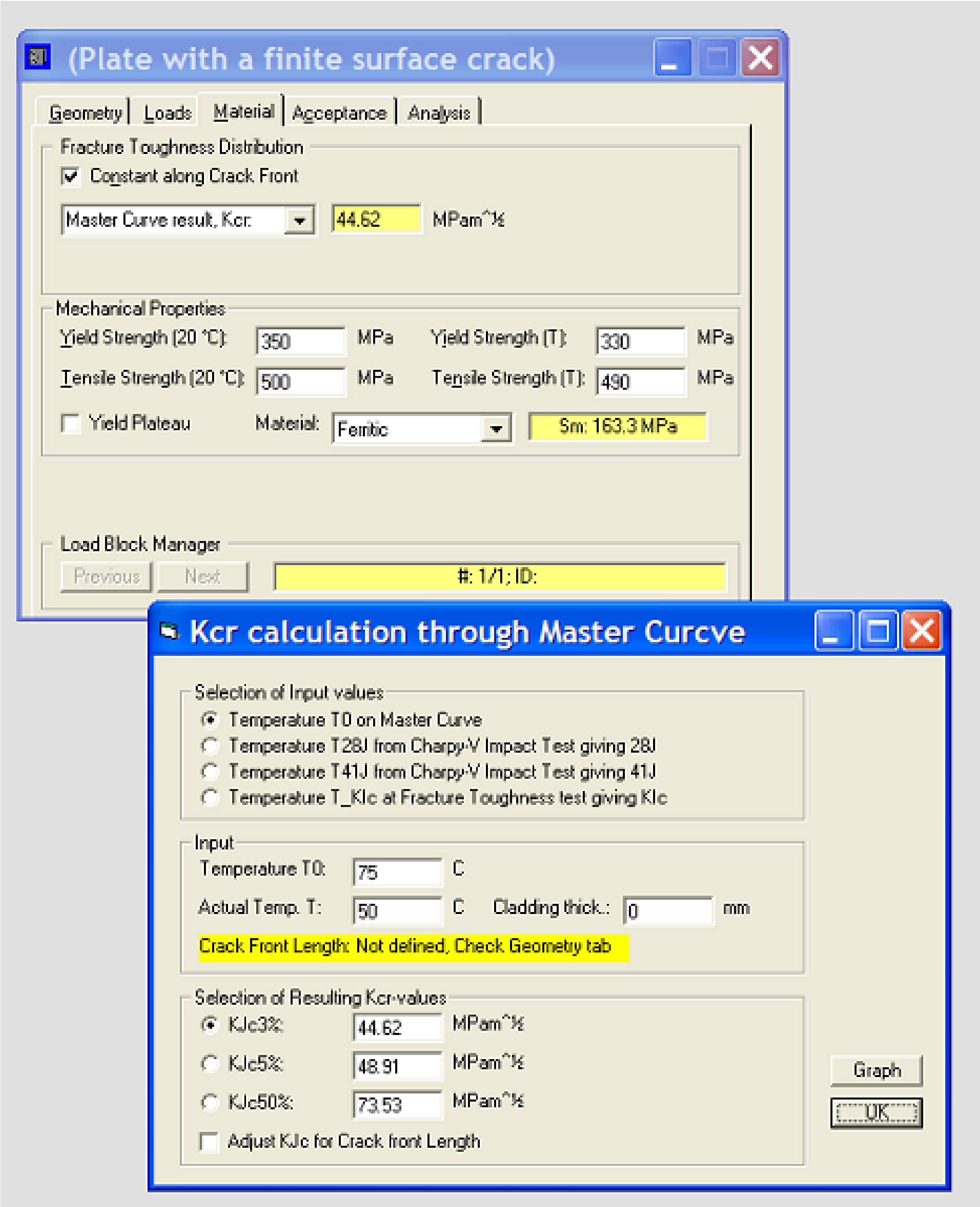


Fig. 3.2: Material box, results of Master Curve toughness for 3% fracture probability.

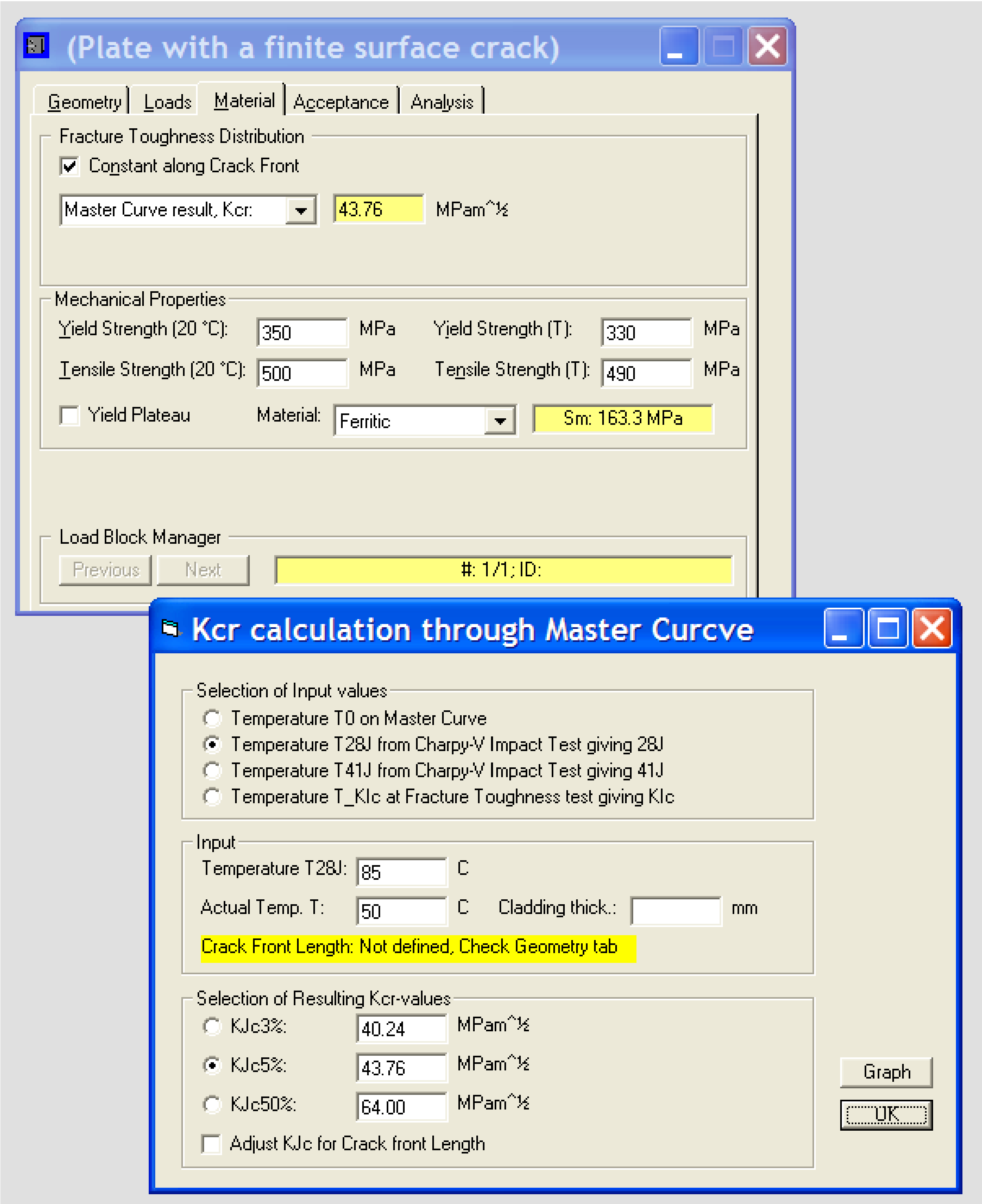


Fig. 3.3: Material box, results of Master Curve toughness with choosing T_{28J} and 5% fracture probability.

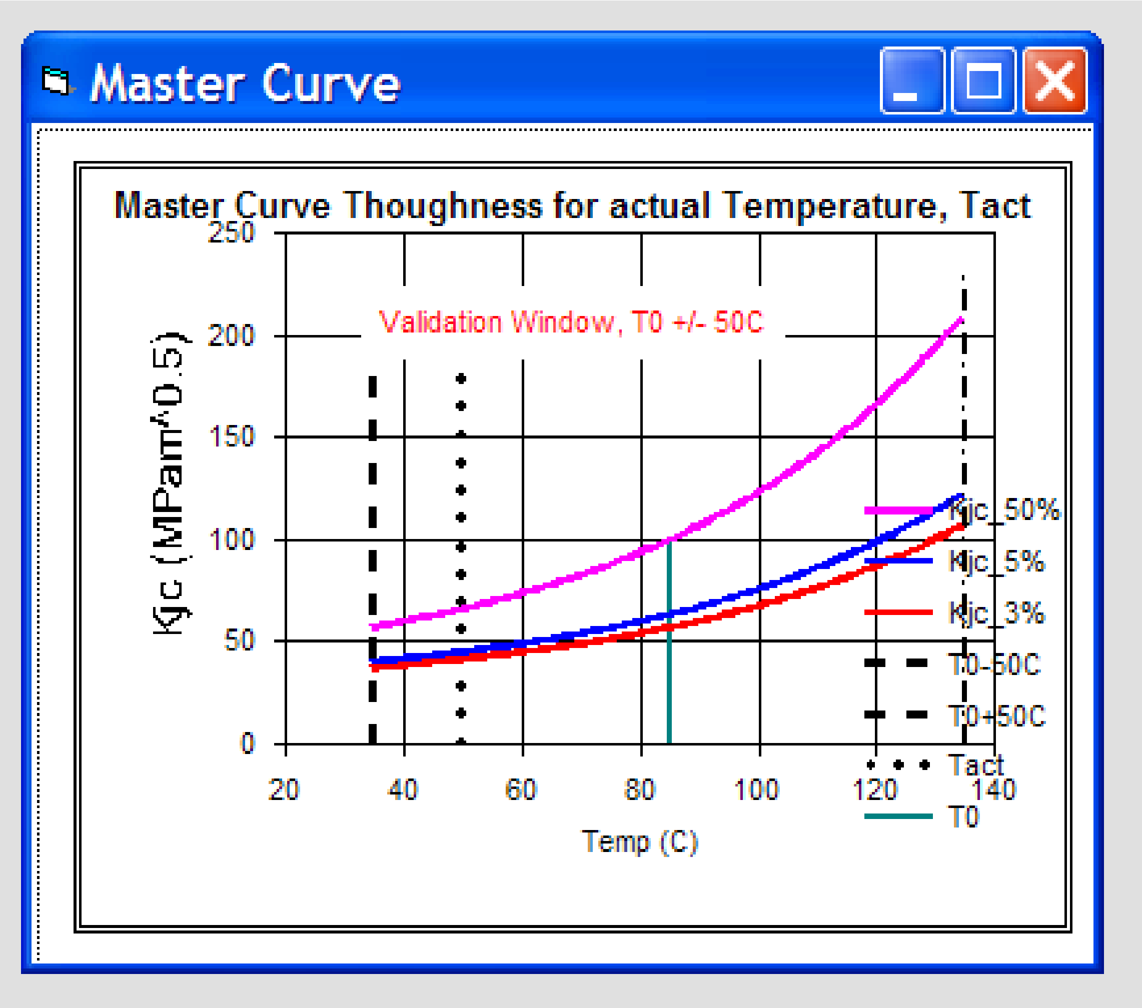


Fig. 3.4: Evaluated results in an Application window of Master Curve toughness.

3.2 CORRECTION FOR CRACK-FRONT SIZE

Within the program, there is the possibility to adjust the K_{JC} value for the crack front length. If the component is clad, the cladding thickness should be given as input in the material box. If there is no cladding, the value of the cladding thickness should be given as zero. Corrections for different crack configurations are considered in the program. It is assumed that the size-correction due to crack-front-length (*cfl*) is valid for crack front length between 25 and 100 mm. It implies that no benefits on fracture toughness increase due to short cracks (*cfl* < 25 mm) are accounted in the program. For *cfl* >100 mm, it is assumed that *cfl* =100 mm, Sattari-Far and Wallin [2005]. Equation (12) gives the fracture toughness values corrected for the crack-front-length.

$$K_{JC}^{cfl} = 20 + \left[K_{JC}^{1T} - 20\right]\left(\frac{25}{cfl}\right)^{1/4} \qquad \text{(12rep)}$$

The values of *cfl* for different crack geometries are obtained from the following procedure.

a) Size correction for through-thickness cracks:

$$cfl = 2t \qquad \text{For components without cladding} \tag{15}$$

$$cfl = 2t - 2t_{clad} \qquad \text{For components with cladding} \tag{16}$$

If $cfl > 100$ mm, it is considered that $cfl = 100$ mm.

If $cfl < 25$ mm, it is considered that $cfl = 25$ mm.

Here, t is the thickness of the component and t_{clad} the thickness of cladding.

b) Size correction for finite surface cracks:

$$cfl = \frac{\pi}{2}\left[3(\mathrm{a} + \mathrm{c}) - \sqrt{10\mathrm{ac} + 3(\mathrm{a}^2 + c^2)}\right] \qquad \text{For components without cladding} \tag{17}$$

$$cfl = \frac{\pi}{2}\left[3(\mathrm{a} + \mathrm{c}) - \sqrt{10\mathrm{ac} + 3(\mathrm{a}^2 + c^2)}\right] - 2t_{clad} \qquad \text{For components with cladding} \tag{18}$$

If $cfl > 100$ mm, it is considered that $cfl = 100$ mm.

If $cfl < 25$ mm, it is considered that $cfl = 25$ mm.

Here, a is crack depth, c half of the crack length and t_{clad} the thickness of cladding.

c) Size correction for embedded cracks:

$$cfl = \pi\left[3(\mathrm{a} + \mathrm{c}) - \sqrt{10\mathrm{ac} + 3(\mathrm{a}^2 + c^2)}\right] \tag{19}$$

If $cfl > 100$ mm, it is considered that $cfl = 100$ mm.

If $cfl < 25$ mm, it is considered that $cfl = 25$ mm.

Here, a is crack depth and c half of the crack length. It is assumed that the crack does not include any cladding.

d) Size correction for infinite cracks:

For long extended (infinite) surface cracks in plates and cylinders (internal and external), the *cfl* is assumed to be 100 mm.

Fig. 3.5 shows the size-corrected fracture toughness value given in Fig. 3.3, now corrected for a crack-front-length of 70 mm. It is observed that due to this correction, the 5% fracture toughness value decreases from 43.76 to 38.37 MPa√m.

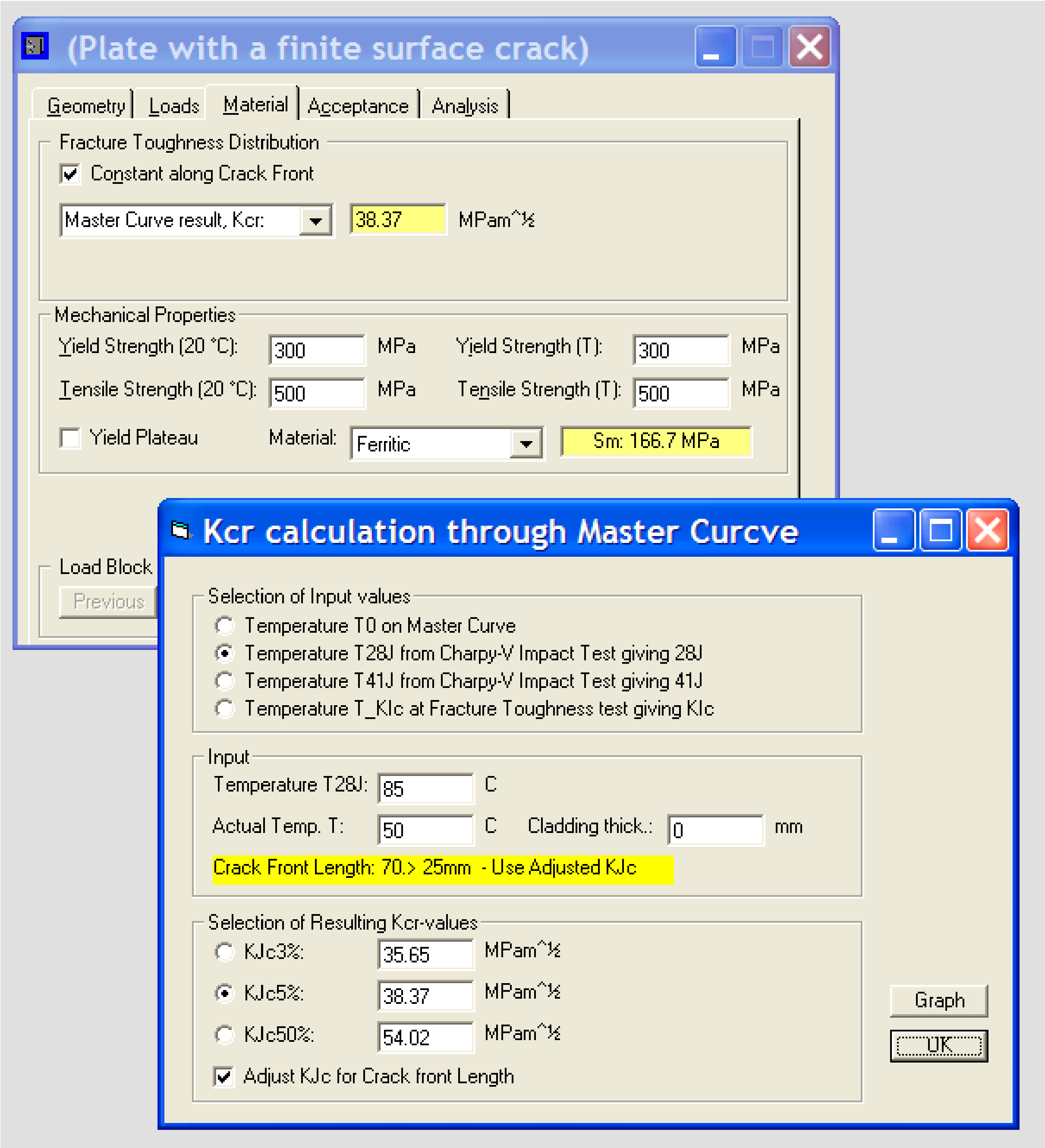


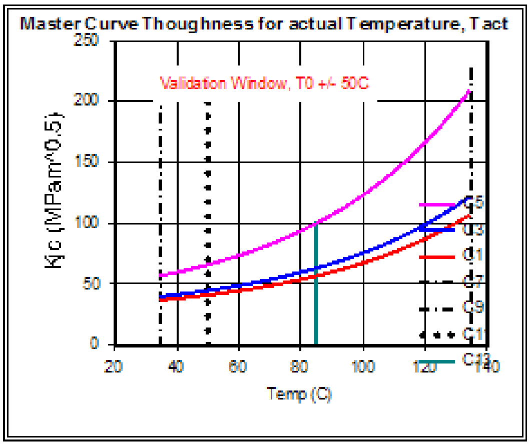
Fig. 3.5: Results of Master Curve toughness with choosing T_{28J} and 5% fracture probability and correction for 70 mm crack-front-length.

The results of the Master Curve evaluation are also presented in the ProSACC final assessment report, as shown in Fig. 3.6. Here, the user gets information on the input-data used for evaluation of Master Curve toughness, and evaluated results within the Master Curve application window.

Material

Load block #: 1/1; ID:

Fracture toughness: 38.37 MPam^½ computed by Master Curve Method with 5% confidence
Correction made for Crack Front Length for thickness excluding the Cladding thickness (0 mm)



Master Curve Method interpolation for temperature: 50C
based on Temperature T28J from Charpy-V Impact Test giving 28J: 85C

Fig. 3.6: Master Curve evaluation results given in the final assessment report of ProSACC.

4 Concluding remarks

1. The main options of the Master Curve methodology are implemented in the ProSACC program.

2. The program gives fracture toughness values at the given temperature based on input data on T_0 from fracture toughness testing, or Charpy impact test results (T_{28J} or T_{41J}) or K_{IC} value from fracture toughness testing on the actual material.

3. There is also a possibility in the program to make crack-size correction on the evaluated fracture toughness.

4. Application of different Master Curve options in ProSACC is illustrated in three examples given in Appendices of this report.

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Appendix A1:
MC calculations when T_0-value is given

For a pressure vessel steel, the Master Curve index temperature is given to be T_0= -5 °C. Determine fracture toughness K_{JC} of this steel at temperatures 10, 40 and 80 °C based on 3%, 5% and 50% fracture probabilities in the Master Curve method.

Solution:

Using Eqns. (7) to (9) gives K_{JC} values presented in Table A1.

Table A1: Fracture toughness K_{JC} [MPa√m] of the steel at different temperatures.

	10 °C	**40 °C**	**80 °C**
K_{JC} -3%	67.4	100.3	186.5
K_{JC} -5%	75.7	114.3	215.4
K_{JC} -50%	123.1	194.6	381.9

Note that the validity window of Master Curve for this steel is T = -55 °C to +45 °C, so T = 80 °C is outside the validation window.

ProSACC gives the same results as in Table A1. The results are given in Fig. A1 for T = 10 °C. The user gets a warning if the actual temperature is outside the validity window.

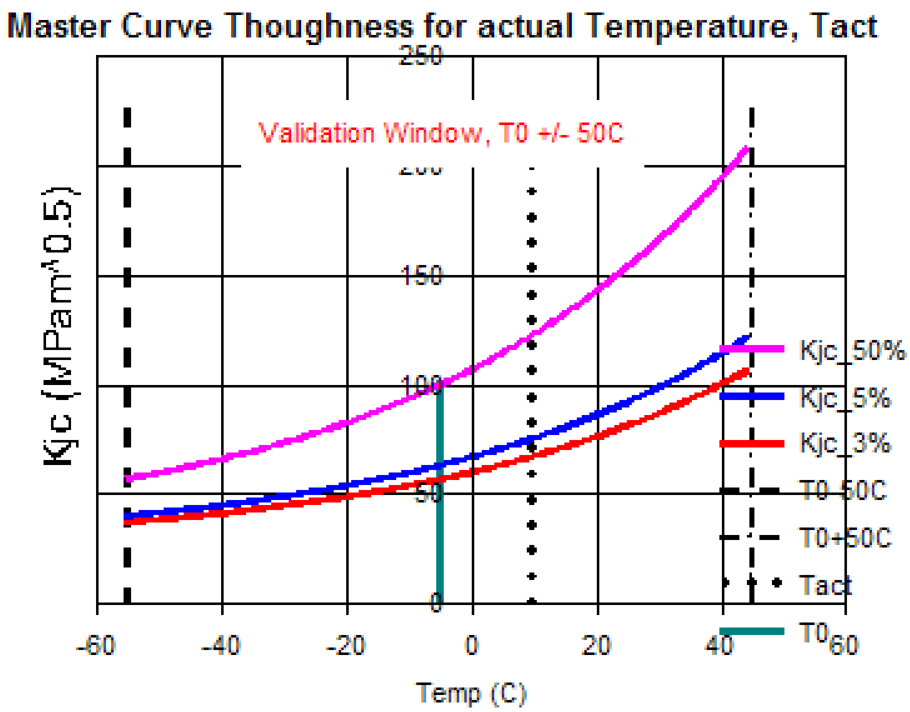

Fig. A1: ProSACC Master Curve fracture toughness evaluations of the steel based on T_0 value.

Appendix A2:
MC calculations when T_{28J}-value is given

From a surveillance test program of a RPV, it is given a value of T_{28J}= 125 °C for a weld. Determine fracture toughness K_{JC} of this weld at temperatures 100 °C and 150 °C to be used for structural assessment of this vessel. The assessment is supposed to be conducted based on 3%, and 5% fracture probabilities.

Solution:

Using Eqn. (13) yields obtaining a conservative value of T_0 for this weld to be T_0 = 128 °C. Using Eqns. (8) and (9) gives conservative K_{JC} values of this weld presented in Table A2.

Table A2: Fracture toughness K_{JC} [MPa√m] of the weld at different temperatures.

	100 °C	150 °C
K_{JC} -3%	43.5	73.5
K_{JC} -5%	47.6	82.8

The actual temperature are within the validity window of Master Curve for this weld that is T = 78 °C to 178 °C. ProSACC gives the same results as in Table A2. The results for T = 100 °C are given in Fig. A2.

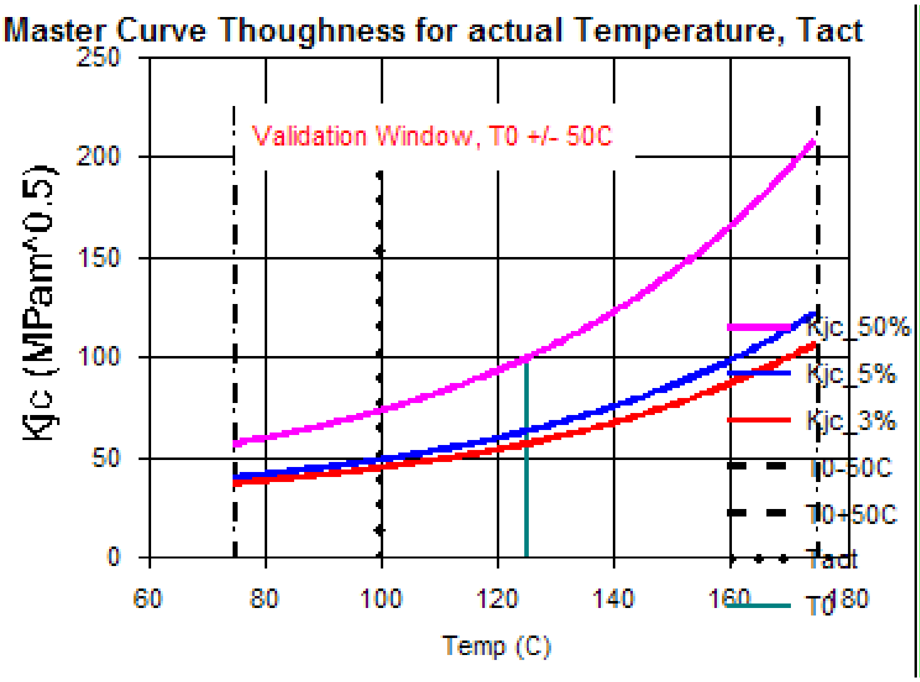

Fig. A2: ProSACC Master Curve fracture toughness evaluations of the weld based on T_{28J} value.

Appendix A3: MC calculations when K_{IC}-value is given

For a RPV material in irradiated state, it is given a value of K_{IC} = 80 MPa√m from standard fracture testing at T = 100 °C. Determine fracture toughness K_{JC} of this material at temperatures 70 and 150 °C to be used for structural integrity assessment of this RPV, assuming to have a surface crack of a = 7 mm and $2c$ = 42 mm. The assessment is supposed to be conducted based on 3%, and 5% fracture probabilities. The vessel is clad with a 4-mm thick stainless steel.

How does the crack length impact the results?

Solution:

Using Eqn. (11) and assuming that the given K_{JC}-value corresponds for K_{JC}(50%), yields obtaining a value of T_0 for this material to be T_0 = 117.7 °C. Using Eqns. (8) and (9) gives standard (25-mm thickness) K_{JC} values of this material as presented in Table A3.

Table A3: Not size-corrected fracture toughness K_{JC} [MPa√m] of the material.

	70 °C	150 °C
K_{JC} -3%	37.6	84.1
K_{JC} -5%	40.7	95.2

The size-corrected K_{JC} results of the material for this crack size assuming cladding and no-cladding are given in Table A4, using Eqns. (12), (17) and (18).

Table A4: Size-corrected fracture toughness K_{JC} [MPa√m] of the material.

	No cladding		With 4 mm cladding	
	70 °C	150 °C	70 °C	150 °C
K_{JC} -3%	35.1	74.8	35.8	77.4
K_{JC} -5%	37.7	84.3	38.5	87.4

As can be seen in Table A4, the cladding has a positive effect in the evaluated fracture toughness, compared with the case without cladding but with the same crack front length.

ProSACC gives the same results as in Tables A3 and A4.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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