INHOMOGENEITY CHECK OF THE "EURO" FRACTURE TOUGHNESS REFERENCE DATA SET

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Abstract

The "EURO" fracture toughness data set is probably the largest comprehensive test for a single material. Previous analysis indicate that the steel in question is very homogeneous. Only one sub-plate appears to have significantly different fracture toughness properties that the others. Until now, no more sophisticated analysis regarding the homogeneity of the material has been performed. Recently, a new extension to the Master Curve technology has been developed, which allows an objective, quantitative, assessment of a materials inhomogeneity. This analysis method has been used here to check the homogeneity of the forging in more detail. The analysis confirm that the major part of the forging is very homogeneous. However, it also reveals a slight bi-modality in the fracture toughness properties. The new analysis method is shown to be extremely efficient for the analysis of large data sets.

Introduction

Probably the largest comprehensive fracture toughness data set for a single material is constituted by the so called "EURO" fracture toughness data set, Heerens and Hellman [1]. The data set has been quite meticulously analysed with the Master Curve (MC) brittle fracture assessment method, Wallin [2]. An example MC analysis of the whole C(T)-specimen data set is presented in Fig. 1. The analysis indicated that the steel in question appears to be exceptionally homogeneous [2]. However, one sub-plate was found to have significantly different fracture toughness properties than the others. At the time, no more detailed assessment of the steels homogeneity was considered necessary.

Recently, new MC analysis algorithms have been developed for the analysis of inhomogeneous data sets, Wallin *et al*. [3]. The algorithms are applicable both for bimodal inhomogeneities as well as random inhomogeneities [3]. The bimodal Master Curve algorithm is especially intended for the analysis of heat affected zone (HAZ) fracture toughness results, which are known to consist of a ductile and brittle constituent. With the new algorithm it may be possible to omit the requirement of making metallurgical sectioning of HAZ test specimens subsequent to testing. The Master Curve algorithm is mostly intended for the analysis of pooled data sets or materials with macroscopic segregations etc. However, they enable also a much more detailed analysis of the EURO data set. Besides comparison between different sub-plates, it is also possible to assess the homogeneity within a single sub-plate.

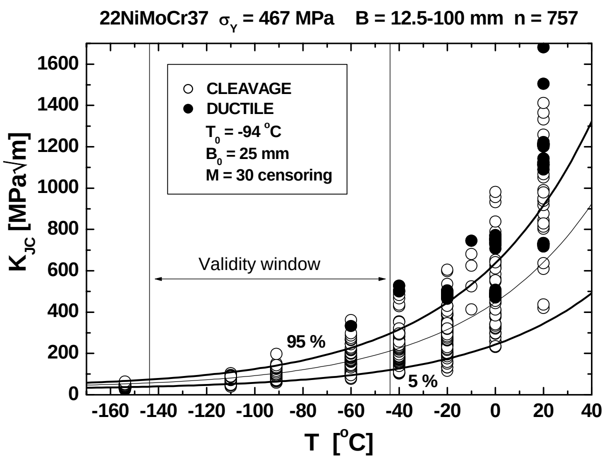


FIGURE 1. Standard MC analysis of the EURO fracture toughness data set.

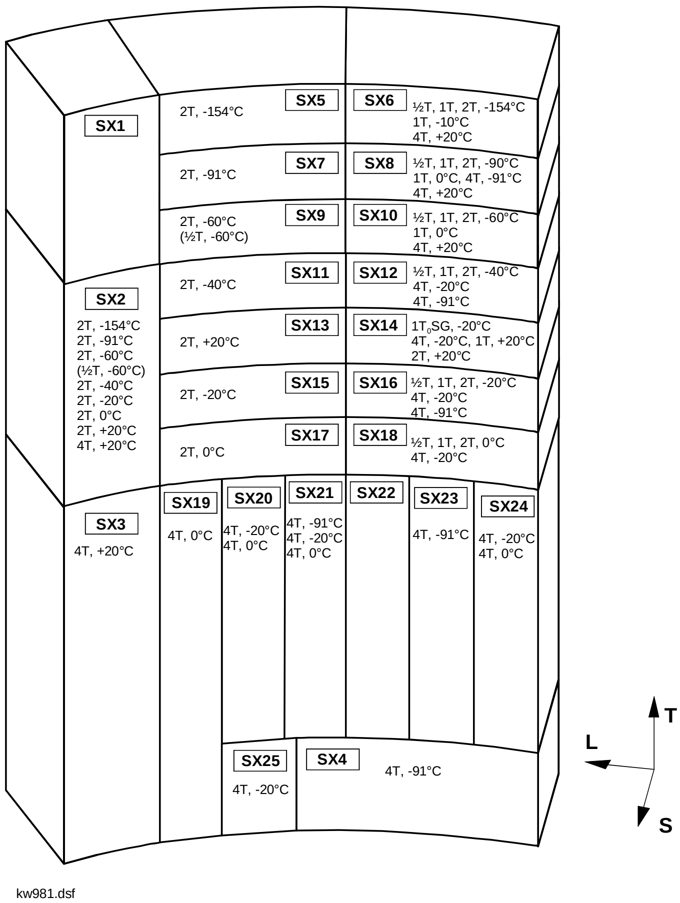


FIGURE 2. Sectioning diagram of the EURO material.

Here, the EURO fracture toughness data set is re-analyzed with the new MC analysis algorithms and the homogeneity of the data set is quantified.

The material

The material was a German pressure vessel steel with designation 22NiMoCr37. All specimens were extracted from a single segment, so that the crack front was located in the region ¼T–½T which had been found to be "homogeneous" in the preliminary investigations performed by GKSS [1]. The segment was divided into several sub-plates. The sectioning diagram is presented in Fig. 2. When each sub-plate is analyzed separately with the standard Master Curve algorithm, not all sub-plates provide valid T_0 values. Fig. 3 shows the result of the standard analysis. Invalid data corresponds to cases where too few results are inside the validity window specified in ASTM E1921-02. However, with the exception of sub-plate SX9, there appears to be only little variation between the sub-plates. The average T_0 value for the "valid" sub-plates is -89ºC which is 5ºC higher than based on an analysis including also the valid data from the "invalid" sub-plates (Fig. 2).

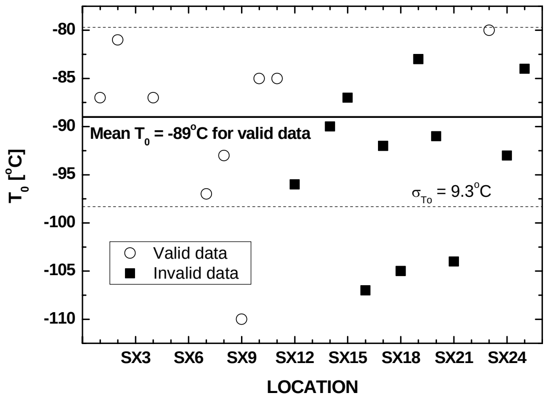


FIGURE 3. Standard MC analysis of different sub-plates.

Bimodal Master Curve [3]

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. This means that the fitting algorithm is somewhat more complicated than in the case of the standard MC. 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

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

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

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

and the survival function has the form

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

The parameters are solved so as to maximize 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).

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

The standard deviation of T_0 for the more brittle material can be approximated by Eq. 6, the more ductile material by Eq. 7 and the uncertainty of the occurence probability of the more brittle material by Eq. 8.

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

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

$$\sigma p_a \approx \frac{0.35}{\sqrt{n \cdot p_a - 2}} \tag{8}$$

In the equations, 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. The minimum data set size to be used with the bimodal distribution is approximately 12-15, but preferably the size should be in excess of 20. Eqs. 6-8 can also be used to judge the likelihood that the data represents an inhomogeneous material. A simple criteria can be expressed as

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

If the criteria in eq. 9 is fulfilled, the material is likely to be significantly inhomogeneous.

Master Curve analysis of random inhomogeneities [3]

The random variable T_0 is assumed to follow a Gaussian distribution characterized by mean T_{0MML} and standard deviation σT_{0MML}. The probability density function for T_0 is in this case

$$f_T = \frac{1}{\sigma T_{0MML} \cdot \sqrt{2\pi}} \cdot \exp\left\{-\frac{\left(T_0 - T_{0MML}\right)^2}{2 \cdot \sigma T_{0MML}^2}\right\} \tag{10}$$

The conditional survival probability at T_0 is the standard MC expression

$$S_{T0} = \exp\left\{-\left(\frac{K_{JC} - K_{\min}}{K_0 - K_{\min}}\right)^4\right\} \tag{11}$$

where K_0 is dependent on T and T_0 according to the standard Master Curve.

The local conditional density probability at T_0 becomes accordingly

$$f_{T0} = 4 \cdot \frac{\left(K_{JC} - K_{\min}\right)^3}{\left(K_0 - K_{\min}\right)^4} \cdot \exp\left\{-\left(\frac{K_{JC} - K_{\min}}{K_0 - K_{\min}}\right)^4\right\} \tag{12}$$

The total survival probability S is obtained by solving the integral

$$S = \int_{-\infty}^{\infty} f_T \cdot S_{T0} \cdot dT_0 \tag{13}$$

and the corresponding total distribution function is

$$f = \int_{-\infty}^{\infty} f_T \cdot f_{T0} \cdot dT_0 \tag{14}$$

The parameters T_{0MML} and σT_{0MML} are then solved by maximizing eq. 5, using eqs. 13 and 14 as input parameters.

A simple criteria to judge the likelihood that the data represents an inhomogeneous material is given by

$$\sigma T_{0MML} > 2 \cdot \sigma T_{0E1921} \tag{15}$$

I.e. the steel is likely to be significantly inhomogeneous if the standard deviation from the MML estimate is bigger than twice the theoretical uncertainty in T_0 for a homogeneous steel.

Results

The analysis results for the sub-plates where there were a sufficient number of non-censored test results are presented in Table 1. In this case, the censoring was only performed with respect to specimens measuring capacity and lower shelf behaviour. The ASTM E1921 validity window was thus not applied as a whole. The sub-plates that the two analysis methods judge to be significantly inhomogeneous are shown in bold in Table 1. The results are also presented graphically in Fig. 4.

The bimodal analysis, using eq. 9, indicated that sub-plates SX8 and SX10 are somewhat inhomogeneous and SX9 clearly inhomogeneous. The random analysis estimates more sub-plates to be statistically significantly inhomogeneous, even though only sub-plate SX9 is evaluated to be clearly inhomogeneous. The others are only barely inhomogeneous based on eq. 15. Overall, the forging is found to be quite homogeneous. The inhomogeneity seems to be located mainly in one spot, covered by the neighbouring sub-plates SX8, SX9 and SX10. The average fracture toughness described by T_0 is very close to -90ºC. Thus the standard Master Curve analysis of the whole data set yielding T_0 = -94ºC and the analysis based on standard Master Curve for the individual sub-plates yielding T_0 = -89ºC are very well in line with the more sophisticated inhomogeneous analysis methods applied here.

The two inhomogeneous analysis methods produce quite consistent descriptions of the materials inhomogeneity (Fig. 4). In this respect, both methods could well be used to characterise the material. The fitting algorithms required for the use of the inhomogeneous Master Curve analysis are unfortunately too complicated to be included in a simple testing standard and also their general application in structural integrity analysis may still be too early. A more simple assessment method, especially designed for structural integrity applications, is constituted by the European SINTAP three step Master Curve analysis [3].

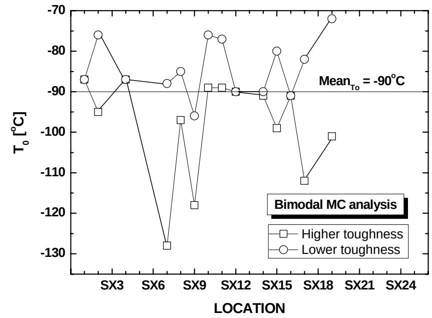
TABLE 1. Inhomogeneous Master Curve analysis.

	Non-censored	"Bimodal" Master Curve			"Random" Master Curve	
Sub-plate	r	p_a [%]	T_{01} [ºC]	T_{02} [ºC]	T_{0av} [ºC]	σT_0 [ºC]
SX1	11	2[1]	-87	-87	-87	1.4
SX2	30	23	-95	-76	**-81**	**8.2**
SX4	28	16[1]	-87	-87	-87	1.4
SX7	24	5	-128	-88	**-92**	**9.0**
SX8	70	**65**	**-97**	**-85**	**-94**	**4.7**
SX9	30	**48**	**-118**	**-96**	**-106**	**11.3**
SX10	77	**68**	**-89**	**-76**	**-85**	**5.0**
SX11	24	55	-89	-77	-84	5.6
SX12	43	7[1]	-90	-90	-90	0.0
SX14	11	17[1]	-91	-90	-90	2.1
SX15	24	23	-99	-80	**-84**	**9.4**
SX16	20	4[1]	-91	-91	-91	1.4
SX17	14	39	-112	-82	**-95**	**10**
SX19	9	17	-101	-72	-79	11.3

[1]Percentage is meaningless since the T_0 estimates are the same.
Bold numbers indicate statistically significant inhomogeneity.

Summary and conclusions

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. Here, the EURO fracture toughness data set has been analysed by two new inhomogeneous Master Curve algorithms. Both methods are shown to provide a consistent description of the material and confirm that the EURO material is overall homogeneous. Only sub-plates SX8-SX10 indicate a significant inhomogeneity. The algorithms may still be too advanced for standard practice, but for structural integrity assessment, the European SINTAP method can be used in stead.



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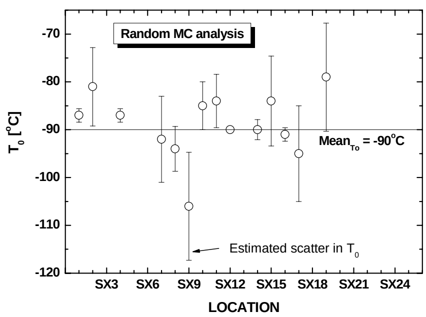

b)

FIGURE 4. Outcome of inhomogeneity analysis.

Acknowledgements

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