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Demonstration of freedom from brittle fracture – Validation of the Master Curve Methodology for Deriving Material Fracture Toughness.

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INTRODUCTION

ASTM A 350 LF5 steel is used in the manufacture of transport flasks. In order to satisfy regulatory requirements for demonstrating this materials' resistance to brittle fracture during flask operation, fracture mechanics data are required. The normal requirement for generating fracture toughness data is that testing must be carried out on material of equivalent thickness to the component under investigation and that the test must be carried out at the appropriate temperature and loading rate. Satisfying these requirements becomes very difficult for thick materials. In particular, routine dynamic testing of 300 mm thick steels could not be done on any known facility and would require a significant effort to develop one.

The Master Curve proposed by Wallin(1) offers an alternative testing philosophy that enables the desired fracture toughness data to be generated by small scale testing.

This report presents the results of a program of work to demonstrate that A350 LF5 steel is amenable to Master Curve techniques.

THE MASTER CURVE

The main features of the Master Curve are outlined below. For a more detailed understanding of it, reference should be made to the original work of.Wallin and co-workers (1-4).

The main objective of that work was the development of a theory to explain the observations surrounding brittle fracture in ferritic steels. Wallin introduced the weakest-link fracture process and was able to demonstrate that the statistical variation of fracture could be described by a three parameter Weibull distribution in which two of the parameters (the shape and shift parameters) are fixed. Furthermore, he introduced the concept of a Master Curve in which the shape of the transition curve is fixed but its position along the temperature axis is material dependent. The "Master Curve" itself defines the variation of the median value of fracture toughness with temperature.

The key fracture toughness parameter that is used to position the curve is the T_0 reference temperature derived from fracture toughness tests.. The T_0 reference temperature is defined as the temperature at which 25 mm thick material has a median fracture toughness of 100 MPam $^{0.5}$. Since the approach is based on weak link fracture model, fracture toughness is specimen size dependent (actually dependent on crack front length). However, results from one specimen thickness can be easily transformed to another thickness by using the fixed shape and shift parameters defined by the Weibull distribution. The test procedure for the derivation of these fracture toughness parameters is ASTM E 1921, which also describes the construction of the "Master Curve".

Further developments of the procedure enabled estimation of fracture toughness at a dynamic loading rate from fracture toughness tests conducted at a quasi static loading rate. The theory predicts that T_0 increases with both increases in specimen thickness and testing rate; as observed by experiment. . Equation (1) is the three parameter Weibull distribution with the fixed shape parameter of 4 and shift parameter of 20 MPam$^{0.5}$ .The shift parameter represents the absolute minimum fracture toughness for ferritic steels. K_0 is the scale parameter (the 63rd percentile of the toughness distribution) that needs to determined experimentally. P(K) is the cumulative probability of fracture toughness, K (MPa m $^{0.5}$).

$$(1) \qquad P(K) = 1 - \exp - \left[\frac{K - 20}{K_0 - 20} \right]^4$$

The Master Curve is given by Equation (2)

$$(2) \qquad K_0 = 31 + 77\exp[0.019(T - T_0)]$$

Equation (3) describes the thickness effect.

(3) $K_{B2} = K_{min} + (K_{B1} – K_{min})(B_1/B_2)^{0.25}$
Where K_{B2} is the fracture toughness to be calculated for thickness B_2, K_{B1} is the fracture toughness for thickness B_1, and K_{min} is minimum fracture toughness, which is conventionally assumed to be 20 MPa.m $^{0.5}$.

Equations (1), (2) and (3) can be combined to provide fracture toughness at a given probability level, specimen thickness and temperature, as shown by Equation (4)

(4) $$K = 20 + \left(11 + 77\exp\left[0.019\left(T - T_0\right)\right]\right)\left(\frac{25}{B}\right)^{0.25}\left(-\ln\left(1 - P_f\right)\right)^{0.25}$$

Where P_f is a probability function.

Equations (5) and (6) describe the strain rate or loading rate effect.

(5) $\Delta T_0 = (T_{01} \ln(\acute{K}_1)/(\Gamma - \ln(\acute{K}_1)$

Where $\acute{K}_1$ is the loading rate in terms of MPa.m $^{0.5}$.s^{-1}, T_{01} is T_0 expressed in K (Kelvin) and Γ , the "Zener-Holloman" parameter, is given by Equation (6),

(6) $\Gamma = 9.9\exp\{(T_{01} /190)^{1.66} +(R_{eL} / 722)^{1.09}\}$

Where R_{eL} = lower room temperature lower yield strength

These “Master Curve” procedures have been validated for a number of steels and the procedures have gained widespread acceptance. They are now encapsulated in a number of national standards and authoritative documents [i.e. ASTM E 1921, BS 7910, SINTAP (4).].

TESTING PROGRAMME

On behalf of BNFL TWI Ltd carried out the fracture toughness test programme on a large base forging left over from a flask manufacturing programme. The A350 LF5 forging was a disk 345mm thick and approximately 900 mm in diameter. The material was given a stress relief heat-treatment to simulate the thermal treatment that would be carried out during flask manufacture. The main elements of the program of work that have a direct bearing on the Master Curve validation were as follows:

i. Quasi-static fracture toughness testing of 25 mm thick test pieces to determine the reference temperature T_0 in accordance with ASTM E 1921.
ii. Dynamic fracture toughness testing of 25 mm thick test pieces to determine the dynamic reference temperature, $T_{0(D)}$.
iii. Quasi-static fracture toughness testing of 100 mm thick fracture toughness test pieces. The test temperature was -105°C.
iv. The use of the Master Curve procedure to calculate the change in T_0, ΔT_0, due to testing at a higher strain rate. The approximate strain rate for transport flask impact loading is 6000 MPa.m $^{0.5}$.s^{-1} and the stain rate obtained in testing was an average of 4789 MPa.m $^{0.5}$.s^{-1}.
v. Comparison between the dynamic reference temperature $T_{0(D)}$ from testing and the theoretically calculated value.
vi. The use of the Master Curve thickness calculation to derive 100 mm fracture toughness from the 25 mm quasi-static test results.
vii. Comparison between the 100 mm quasi-static test results and 100 mm results derived from the 25 mm quasi-static tests results.

RESULTS

Fracture toughness test results are presented in Table 1 and further details are given under the following sub-headings

Quasi-static Fracture Toughness Testing of 25 mm Test Pieces in Accordance With ASTM E 1921

The ASTM E 1921 procedure requires the testing of at least six 25 mm thick specimens at a temperature which is close to the reference temperature T_0. After conducting some preliminary tests, -105°C was selected as the test temperature for the determination of T_0.

Under quasi-static loading the tests provided a T_0 estimate of –145°C.

T_0 was used to construct the transition curve presented in Figure 1. In this figure, the median curve ($P_f = 0.5$) is plotted along with the 95% and 5% confidence curves (i.e. for the 95% curve, 95% of fracture toughness values lie below the curve or in the case of the 5% curve, 95% of fracture toughness values will lie above the curve)

Dynamic Fracture Toughness Testing of 25 mm Test Pieces in Accordance With ASTM E 1921

The procedure for the dynamic fracture toughness testing was similar to that reported above for the static tests. The test temperature was chosen using Equation (5) together with T_0 estimated from the quasi static tests.. The temperature chosen for the dynamic fracture toughness tests was -68°C. The average dynamic rate was 4789 $MPa.m^{0.5}.s^{-1}$. This compared favourably with the anticipated rate for impact events in thick walled flasks, which was 6000 . $MPa.m^{0.5}.s^{-1}$

The six 25 mm thick fracture toughness tests were used to determine the reference temperature and the Median value of fracture toughness. The result was:

$$T_{0(D)} = -73°C$$

The temperature shift, in 25mm thick material, due to testing at the dynamic rate of 4789 $MPa.m^{0.5}.s^{-1}$ may now be determined. I.e.:

$$\Delta T_0 = T_{0(D)} - T_0 = -73 - (-145) = 72°C$$

Quasi-static Fracture Toughness Testing of 100mm Thick Material

The purpose of the 100 mm thick fracture toughness tests was to provide thick material test data against which the Master Curve thickness calculation could be verified. The same test temperature as the 25 mm thick static tests was used, namely –105°C.. The results are presented in Table 1.

Theoretical Calculation of ΔT_0 Using Master Curve Procedures

The estimation of ΔT_0 was carried out using Equations (5) and (6):
For a stress intensity rate, $\acute{K}_1$, of 4789 $MPa.m^{0.5}.s^{-1}$, a lower yield strength, R_{eL}, of 260 MPa and quasi-static value of T_0 = -145°C (T_{01} = 128 Kelvin), ΔT_0 = 74°C.

Theoretical Calculation of the Fracture Toughness of 100 mm Thick Material from 25 mm Tests.

The fracture toughness of the 100mm thick material was estimated from the fracture toughness from tests on the 25mm thick material using Equation (3) .

The results are given in the Table 2 and Figure 2.The estimated fracture toughness and fracture toughness results from 100 mm thick tests are also plotted in Figure 2 on the 25 mm static Master Curve.

In Figure 2 the two groups overlap showing that the agreement between tested and computed 100 mm fracture toughness is good. However, the 100 mm fracture toughness tests results, taken as a group produced a higher fracture toughness than the calculated values, taken as a group, suggesting that the computation of fracture toughness for thicker material using Equation (3) produces conservative results.

DISCUSSION

The comparison of the predicted temperature shift and actual temperature shift due to dynamic loading produced excellent results. Predicted $\Delta T_0 = 74°C$ and actual $\Delta T_0 = 72°C$. It should be noted that the dynamic rates used for the tests were based on actual rates obtained from transport flask impact modelling. If, for some future design of flask, higher loading rates have to be accommodated, further validation work may be required. However, there are indications from preliminary work not reported here that at rates 10 times higher, the theoretical ΔT_0 equation (Equation 5) is conservative with respect to 25mm thick dynamic fracture toughness test data on this material.

The comparison between the 100 mm thick fracture toughness result calculated from 25 mm test results and the 100 mm fracture toughness test results again produced an excellent correlation. The calculated and actual test results exhibited considerable overlap. In terms of the median values for each group, the predicted result was 133 $MPa.m^{0.5}$ and was lower than the actual result, 143 $MPa.m^{0.5}$. Use of Equation (3) is therefore conservative. The simple average values were 117 and 145 $MPa.m^{0.5}$ respectively.

The practical use of the curves to derive values of fracture toughness for use in structural integrity assessments for flasks would probably entail:

(a) Experimental determination on T_0 according ASTM E1921, using the temperature shift equation for allow for dynamic effects and –

(b) The Master Curve (Equation 4) to determine fracture toughness at different temperatures.

Guidance on the use of an appropriate value of fracture toughness for analysis is given in BS 7910. This recommends the mean value minus one standard deviation for use in analysis. This can be estimated from the Weibull distribution, as described in ASTM E 1921. The mean minus one standard deviation curve is shown in Figure 3, superimposed on the median, 5% and 95% probability curves constructed from the 25 mm dynamic test results. However, as the fracture toughness values derived in this way are based on a weak link fracture model, consideration should be given to correcting for crack front length rather than material thickness when conducting structural integrity assessments into flaw significance.

CONCLUSIONS

This programme of work has demonstrated that A350 LF5 steel is amenable to treatment using the Master Curve approach. In particular:

The Master Curve adjustment to accommodate dynamic loading rates, $\Delta T_0 = (T_{01} \ln(\acute{K}_1)/(\Gamma - \ln(\acute{K}_1)$, was found to be valid for A350 LF5 steel for stress intensity rates, $\acute{K}_1$, up to 4789 $MPa.m^{0.5}.s^{-1}$.

The Master Curve adjustment for thickness, $K_{B2} = K_{min} + (K_{B1} - K_{min})(B_1/B_2)^{0.25}$, was found to be valid for A350 LF5 steel for thicknesses up to 100mm.

Master Curve procedures may be used to calculate the fracture toughness for thick material from tests on thinner material.

REFERENCES

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Test Type	Specimen Detail	Temp (°C)	J_0 (N/mm)	$K_{(J)}$ (MPa.m$^{0.5}$)	$\acute{K}$ (MPa m$^{0.5}$s^{-1})
Static Tests	25x50 SENB	-105	30.3	83.0	
		-105	141.0	179.1	
		-105	29.6	82.1	
		-105	120.7	165.7	
		-105	120.6	165.6	
		-105	324.5	271.7	
	100x100 SENB	-105	135.0	175.2	
		-105	110.6	158.6	
		-105	96.7	148.3	
		-105	55.5	112.4	
		-105	142.2	179.8	
		-105	43.2	99.1	
Dynamic Tests	25x50 SENB	-68	58.4	115.3	5183
		-68	51.2	108.0	4673
		-68	71.6	127.6	4548
		-68	75.6	131.2	3698
		-68	11.1	50.2	4760
		-68	54.1	111.0	5869

Table 1 Fracture toughness test results from the TWI test program

K_{min} (MPa.m$^{0.5}$)	K_{B1} (MPa.m$^{0.5}$)	B_1 (mm)	B_2 (mm)	K_{B2} (MPa.m$^{0.5}$)
20	83.0	25	100	64.5
20	179.1	25	100	132.5
20	82.1	25	100	63.9
20	165.7	25	100	123.0
20	165.6	25	100	123.0
20	271.7	25	100	198.0

Table 2 100 mm fracture toughness values calculated from the 25 mm static test results given in Table 1.

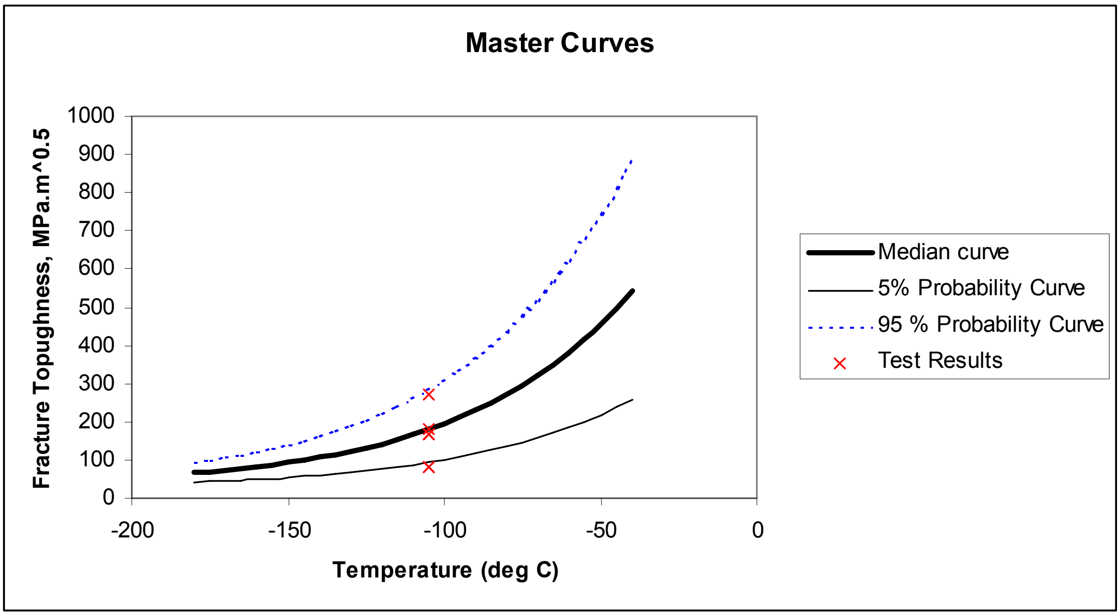

Figure 1 The Master Curve construction for the 25 mm quasi static tests for T_0 = -145°C. The 5% and 95% probability limits are also shown. The effect of dynamic loading rates on the above would be to shift the curve by an amount ΔT to the right along the Temperature axis.

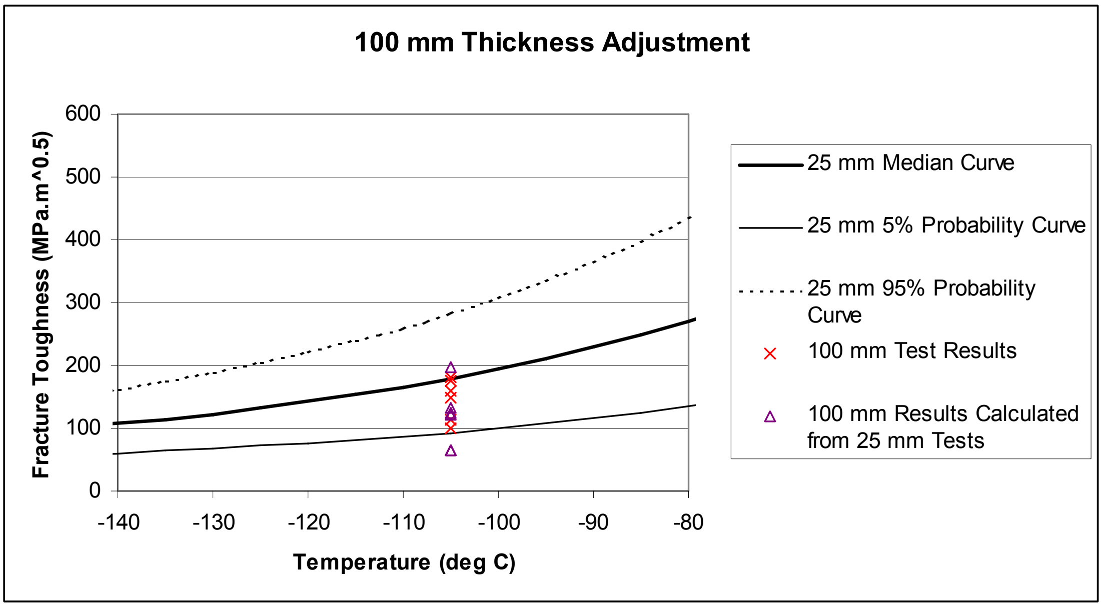

Figure 2 The 100 mm test results and the 100 mm calculated results overlap showing good correlation. As a group, the calculated results are lower. Both sets lie below the curves drawn for the static 25 mm tests. To fit these results to the curve, it would have to be moved to the right along the temperature axis.

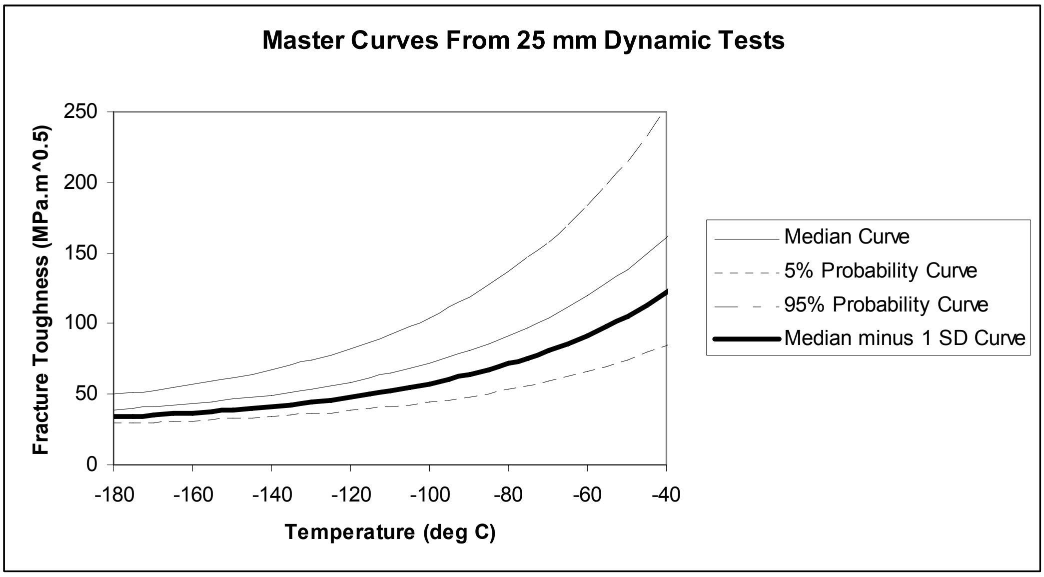

Figure 3 Master Curve construction using the 25 mm dynamic test results showing the mean minus 1 SD curve.