Influence of Specimen Size on the Upper Shelf Toughness of SA A533B-1 Steel

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ABSTRACT

Results are presented from an experimental programme on a 150mm thick plate of A533B Class 1 steel, aimed at enlarging the data base concerning the influence of specimen thickness on upper shelf initiation toughness and resistance to crack growth. The programme involves multiple specimen J_R testing at both ambient temperature and 288ºC using plain and side-grooved compact specimens with thicknesses ranging from 10mm to 100mm.

The multiple specimen data have been assessed using both linear and non-linear J_R construction procedures. In general, linear analyses produce initiation toughness (J_I) and resistance to crack growth (dJ_R/da) data which are very sensitive to the range of crack growth. Power curve analyses provide a better representation of upper shelf behaviour. Comparison of different estimates of initiation toughness has shown that defining initiation toughness as the value of J at Δa = 0.2mm from a power law J_R analysis provides values which, for engineering application, can be considered to be size independent.

A power law analysis provides a better representation of resistance to crack growth than linear analyses. Size independent J_R curves are obtained only for 40mm and 100mm thick specimens. For smaller, 10mm and 20mm thick specimens, the slope of the J_R curve increases as specimen size decreases although the effect is small and can be minimised by side-grooving.

The results indicate that when J_R data are represented by a power law analysis, current requirements for defining size independent initiation toughness values (Δa, B, b ≥ 25-50 J_R/σ_f) and resistance to crack growth data (a, B, b ≥ 20-25 J_max/σ_f, Δa ≤ 6-10% b) could be relaxed to a, B, b ≥ 20 J_R/σ_f, 15 J_max/σ_f and Δa ≤ 15% b.
1. Introduction

Structural integrity assessments pertaining to fully ductile behaviour involve the determination of both the toughness at the onset of macroscopic ductile crack extension (initiation toughness) and the effective increase in toughness which accompanies stable crack growth (resistance to crack growth). Initiation toughness and resistance to crack growth data are inter-related but at present there is no single "standard" test method which will provide size independent values of both parameters.

The minimum specimen size requirements for producing size independent upper shelf toughness values are not well-established. Theoretical considerations and experimental finite element studies\(^1\,2\,3\) indicate that size independence will be achieved when:

\[
\begin{align*}
\text{a, b > } M_1 \frac{J_c}{\sigma_f} & \quad \text{ where } M_1 = 25-50 \\
\text{a, b > } M_2 \frac{J_{\text{max}}}{\sigma_f} & \quad \text{ where } M_2 = 15-25 \\
\Delta a \leq x \% b & \quad \text{ where } x = 6-10 \\
\omega = \frac{b}{d} \frac{dJ}{da} & > 5-10
\end{align*}
\]

These requirements have been embodied in an ASTM standard method for initiation toughness \((J_{\text{IC}})\) measurement \((M_1 = 25, M_2 = 15)\)\(^4\) and a tentative ASTM method for measuring a plane strain \(J_{\text{IC}}\) curve \((M_2 = 20, x = 10, \omega > 5)\)\(^5\). It is now recognised that for steels which develop high resistance to crack growth, the ASTM \(J_{\text{IC}}\) method provides a measurement of toughness which is associated with a small \((< 0.5\text{mm})\) but variable increment of ductile crack growth rather than that at the onset of ductile crack initiation\(6\,7\). For this reason, some workers used alternative methods when attempting to define initiation toughness values\(6\,8\,9\).

An experimental programme was initiated at Risley Nuclear Power Development Laboratories (RNPD) to examine the influence of specimen size and geometry on both initiation toughness and resistance to crack growth. The programme is based upon multiple specimen \(J_{\text{c}}\) testing. This paper summarises the results from that part of the programme concerning the influence of thickness on upper shelf toughness.

2. Objective

The objective of the programme was to test 2U, 20, 4U and 100mm thick compact specimens at the onset of upper shelf conditions and \(280^\circ\text{C}\) to examine the influence of specimen thickness and side-grooving on upper shelf toughness data, defined by different \(J_{\text{c}}\) construction procedures.

3. Material and Specimen Preparation

Specimens were manufactured from a 150mm thick A533B Class 1 plate produced commercially using selected scrap, double slag refining and vacuum de-gassing. After austenitising for 4hrs 50mins at \(895^\circ\text{C}\), the plate was water quenched, tempered for 5hrs 15mins at \(650^\circ\text{C}\) and subsequently stress relieved for 25hrs at \(615 \pm 10^\circ\text{C}\). The chemical composition of the plate (heat analysis) is given in Table I. The steel meets the chemistry requirements for nuclear pressure vessel butt-line materials.

Standard tensile properties and Charpy V notch impact data were obtained at 5 equi-spaced locations through the thickness of the plate using the plate centre-line as a reference. Average values of the longitudinal (L) tensile properties and upper shelf Charpy impact data for the L-T orientation are given in Table II.

The compact specimens were extracted from the plate in the L-T (R-W) orientation. The 100mm thick specimens were machined with the specimen centre-line at plate mid-thickness. Smaller \((10, 20, 40\text{mm})\) specimens were extracted at different levels within the plate so that, for each size, specimens were obtained from the whole of the through thickness region of the plate sampled by the 100mm specimens. All specimens were fatigue pre-cracked to an a/W ratio of 0.6.

4. Experimental Procedure

For convenience, the temperature for the onset of upper shelf conditions was taken as ambient temperature. All specimens exhibited fully ductile behaviour at this temperature.
Tests at 288°C on 10, 20 and 40mm thick specimens were conducted in an air circulating furnace and heater tapes were used to heat the 100mm thick specimens. Water cooled clip gauges were used for all tests at 288°C.

Values of J were calculated using:

\[ J = 2A/B(\pi c)^2f(\sigma_0/\mu) \{ 1 - \frac{0.75f(\sigma_0/\mu)}{b} \} \]

Values of crack growth, \( \Delta a \), were obtained using the ASTM E813:81 weighted average ie

\[ \Delta a = \frac{(\Delta a_1 + \Delta a_3)/2 + \Delta a_2 + \Delta a_3 + \ldots + \Delta a_g}{g} \]

5. Methods of Analysis

J-\( \Delta a \) data from the interrupted tests were analysed using the following J-\( \Delta a \) constructions:

(i) Linear regression analyses on J-\( \Delta a \) data within the range \( \Delta a \sim 0.2 \text{mm} \leq \Delta a \leq 0.06b \) or \( \Delta a \sim 0.2 \text{mm} < \Delta a < 2 \text{mm} \).

(ii) Linear regressions on data lying within the \( \Delta a \) range specified in the ASTM E813:81 procedure for determining JIC.

(iii) Power law curve fits.

"Initiation" toughness values were defined for each construction as the intersection of the Jc relationship with either a J = 40\( \Delta a \) or a J = 40\( \Delta a \) blunting line. For power law analyses, "initiation" values were also defined at the intersection of the Jc curve and a line offset 0.1mm from a J = 40\( \Delta a \) blunting line or a fixed increment of crack growth (including blunting) of 0.2mm. Initiation toughness values are referred to as J0, JIC from the analyses based on E813:81 or as J with an appropriate subscript to indicate the method of defining "initiation" (ie type of blunting line assumption or value of J at \( \Delta a = 0.2 \text{mm} \)). The slopes, dJ/d\( \Delta a \), of the various Jc constructions, which provide a measure of resistance to crack growth have been expressed in terms of the tear modulus, J = E/\( \gamma c^2dJ/d\sigma_a \), in order to normalise the influence on Jc of the change in plastic flow properties with test temperature.

6. Results and Discussion

Estimates of "initiation" toughness from linear and power law Jc constructions are compared in Figures 1 and 2 respectively. Values of Tearing Modulus from the different Jc constructions are compared in Figure 3.

6.1 Initiation toughness

Earlier studies[6,10] have demonstrated that for LWR materials realistic values of initiation toughness are obtained from 20-40mm thick specimens when the onset of ductile crack growth is defined by the intersection of a J = 40\( \Delta a \) blunting line and a linear J-\( \Delta a \) analysis for data where \( \Delta a \lesssim 2 \text{mm} \). Such data (identified here as J40\( \Delta a \)) were used to provide a data-base of upper shelf toughness values for a detailed assessment of the integrity of LWR pressure vessels[11]. In the work reported here, the initiation values for 20mm and 40mm thick specimens defined in this manner have been used as datum levels to assess different Jc construction procedures and specimen thickness effects.

6.1.1 Linear analyses (Figure 1)

Initiation values were only defined for a particular Jc construction when at least 4 J-\( \Delta a \) data points were available within the specified \( \Delta a \) range.

The scatter in initiation toughness values for a given linear Jc construction is quite high and complicates a critical evaluation of thickness effects. Comparison of the different initiation estimates in Figure 1(a)-(c) suggests that a J40\( \Delta a \) definition using a \( \Delta a < 2 \text{nm} \) crack growth range provides the least thickness-dependent estimates of initiation toughness. However, the tests at 288°C indicate an increase in these J40\( \Delta a \) values (D) as specimen thickness increases to 100mm (Fig 1c).

Using a linear analysis where \( \Delta a \) is limited by the \( J \) controlled growth requirement,
\( \Delta \leq 0.06 \) produces data (\( * \)) which are markedly size dependent. This can be seen from the JIC values for 10mm and 100mm thick non-side grooved specimens tested at both ambient temperature and 280°C (Figs 1(a) and 1(c)). The effect is directly attributable to the large difference in allowable \( \Delta \) range, 0.48mm and 4.8mm, for the two specimen sizes.

Using a \( J = 2.5 \Delta \) blunting line in conjunction with a JIC relationship for \( \Delta \) values less than 0.06 (or 2mm) provides JIC values which over-estimate the "datum" values, particularly at ambient temperature where resistance to crack growth is highest. The ASTM JIC (JIC) values are also significantly higher than the "datum" toughness levels at 20°C (Fig 1(a), (b)), due to the higher crack growth range and shallower \( J = 2.5 \Delta \) blunting line specified in ASTM E813. In effect, JIC values are associated with a larger increment of growth, \( \Delta \), than corresponding JIC data. Differences between JIC and JIC(JIC) values are reduced at 280°C for the reason noted previously. The ASTM size requirements (\( b > 1.5 \Delta \)) does not preclude a definition of valid JIC values from 10mm and 20mm specimens at 20°C and 10mm specimens at 280°C. Consequently, a strict comparison of the influence of thickness on JIC can be made only for the 40mm and 100mm thick specimens tested at 280°C, which provided JIC values of 0.22 and 0.33MJ/m² respectively. These results are plotted in Figure 4 together with all data for 10mm and 20mm thick specimens which fall within the E813 exclusion lines. The disposition of data points for the 40mm(+) and 100mm(\( \Delta \)) thick specimens show that any influence of size on JIC is, at most, a second order effect; these results illustrate that any interpretation of size effect should take into account the influences of both inherent material variability and differences induced by analytical procedures (for example, the effect of outliers). An analysis of all 'valid' data for 20, 40 and 100mm thick specimens provides a JIC value of 0.24MJ/m²; similar analyses for plane and side-grooved specimens tested at ambient temperature produced JIC values of 0.54 and 0.33MJ/m² respectively. The JIC data from 10mm specimens have been included in Figure 4 to illustrate a problem observed only when specimens of this size were tested at 280°C to achieve levels of crack growth beyond \( \Delta \leq 1.25 \)mm. The large levels of crack growth and \( \Delta \) increase of slip and 

Comparison of Figures 1(a) and (b) shows that side-grooving has little effect on JIC as defined at the JIC(JIC) level using linear constructions where \( \Delta \) is less than either 0.06B or 2mm but produces a larger reduction (0.48 to 0.35MJ/m²) in the JIC value determined from 40mm thick specimens.

6.1.2 Power law analyses (Figure 2)

The over-riding problem in any interpretation of initiation toughness values from linear construction is the high sensitivity to the precise crack growth range used in the analysis. This can be overcome to a large extent if non-linear JIC analyses are used. Figure 2, which compares different estimates of initiation toughness from power law analyses (J = A \( \Delta ^{B} \)) shows that, at ambient temperature, acceptable correspondence with "datum" values is obtained when \( \Delta \) is defined at either a 0.1mm offset from a J = 4.5\( \Delta \) blunting line (JIC 0.1/4.05) or the value of J at \( \Delta \) = 0.2mm (JIC 0.2). A J = 4.5\( \Delta \) intercept with the power curve underpredicts initiation at both ambient temperature and 280°C. Apart from JIC(JIC) values, which consistently underpredict initiation in power-law analyses, all other estimates (JIC 0.1/4.05 and JIC 0.2) are nominally equivalent at 280°C due to the relatively small levels of crack growth and \( \Delta \) increase of slip and 

The power-law analyses also provide the most consistent interpretation of the effect of thickness on initiation toughness. It can be seen from Figure 2 that identical values were obtained from tests at 10mm, 20mm, and 40mm thick specimens. Furthermore, the JIC 0.2 definition provides equivalent initiation values for tests on both non-side-grooved and side-grooved specimens. Although this analysis still indicates an increase in initiation toughness for 100mm thick specimens, the increase is barely significant at the 95% confidence level.

Tests at 280°C provided closer correspondence between initiation data from 100mm thick and small scale specimens than that from similar specimens tested at ambient temperature (Figure 2(a) and 2(c)). In fact, power law analyses provide identical initiation data for 10mm and 100mm thick specimens tested at 280°C if results from the smaller (10mm) specimens where crack growth is inhibited by gross shear are excluded from the analysis. These results
indicate that for practical purposes, initiation toughness values obtained from power curve analyses are essentially thickness-independent over the range tested. Figures 1 and 2 also show the mean and lower 95% confidence limit values of initiation toughness which were defined in reference [11] as "best-estimate" values for modern UHP steels. The $J_{1a} = 0.2$ data derived from power law analyses will be slightly conservative with respect to the initiation data used to define "best-estimate" upper shelf toughness/temperature relationships in ref [11]; these data lie above (ambient temperature) or bound (285°C) the "best-estimate" mean values from ref [11] (Figure 2). Thus the toughness/temperature relationships defined from [11]

\[
\begin{align*}
K^i_{	ext{mean}} &= 231 - 0.096 \, \text{T}^\circ \text{C} \, (K_i \text{ in MPa} \cdot \text{m}) \\
K^i_{-95\text{SCA}} &= 182 - 0.096 \, \text{T}^\circ \text{C}
\end{align*}
\]

should still apply to data derived using power law analyses.

6.2 Resistance to crack growth (Figure 3)

Any linear analysis provides an average value of $T$ for the specific $\Delta a$ range used in the analysis and extrapolation to higher $\Delta a$ values will produce crack growth resistance data which become progressively more non-conservative. A power law interpretation provides a closer representation of overall material response to increasing crack growth than the linear approximations. Comparison of $T$ values at $\Delta a = 1$ and 2mm from power law analyses illustrates that $T$ reduces by 25-50% depending upon specimen size and test temperature as $\Delta a$ increases from 1mm to 2mm. Variations in $T$ will be even higher for the first millimetre of crack growth and it is this factor which introduces practical difficulties when defining initiation toughness values.

Figure 3 shows that resistance to crack growth expressed as the Tearing Modulus, $T$, decreases with increasing upper shelf temperature and with side-grooving. The $T$ values from linear analyses where $\Delta a < 0.06b$ are highly size dependent for the reasons noted when discussing initiation toughness data. $T$ values from power law analyses are constant for tests on 40 and 100mm thick specimens but increase as specimen thickness decreases below 40mm. The size effect diminished as upper shelf temperature increased. Data from tests on side-grooved specimens, Figure 3(b), confirm that by inhibiting shear lip formation, side-grooving increases the $J_R$ measurement capacity for a given specimen size. Thus the degree by which the 10mm thick specimens over-estimate resistance to crack growth in thicker (> 40mm) specimens should be reduced by side-grooving. Support for this statement is given by the results from the analysis for 10mm specimens tested at 285°C where "gross shear" data were excluded, Figure 3(c). In this case $T$ values for 10mm specimens under-estimate corresponding values for 100mm thick specimens. Material variability within the central 100mm of the plate and the number of data analysed for a given specimen size could account for a 10-15% variation in $T$ and no size dependence of $J_R$ must be judged accordingly. It is concluded, therefore, that the actual size dependence of $J_R$ is quite small.

Lower bound estimates of resistance to crack growth for A533B-1 steels were defined in ref [11] as 0.130 and 0.053MJm$^{-2}$/mm at the onset of upper shelf anc 285°C respectively. These data were derived using linear $J$ analyses and apply for up to 2mm crack growth. Figure 3 shows that all $T$ values at $\Delta a = 2$mm for power law analyses (which are more conservative than data from linear analyses for $\Delta a < 2$mm) lie above the corresponding lower bound values.

All results obtained in the test programme are plotted in Figures 5-7. These confirm that the power law interpretation is more appropriate than linear $J$-$\Delta a$ relationships. The power law relationships were derived using test data for each specimen size where $\Delta a < 15$% b. Virtually identical relationships were obtained when $\Delta a$ was limited to 6% and 10% b. The disposition of data points from different specimen sizes supports the absence of any significant size effect on $J_R$; no systematic trend in $J_R$ as a function of thickness being discernible for the first millimetre of crack growth. With regard to resistance to crack growth, size effects appear to be negligible when $\Delta a = 15$% b or 3mm max/mm, whichever is the smaller. The equivalence in $J_R$ data for up to 5mm $\Delta a$ observed in tests on 40mm and 100mm thick size-grooved specimens, Figure 6, suggests that the current $J$ controlled growth requirements $\Delta a < 6$% or 10% b and $b > 20$-25mm for $J_R$ are unduly restrictive. The results indicate that for power law analyses, these requirements could be relaxed to $\Delta a < 15$% b (or 5mm max), $b > 15$mm for $J_R$.

7. Concluding Remarks

A power law analysis provides a better representation of resistance to crack growth than
linear analyses; initiation toughness defined as the value of J at $\Delta a = 0.2\text{mm}$ from the former will provide data which, for engineering purposes, can be considered to be size independent over the thickness range 10-100mm. It can be seen that size requirements for JI determinations in standard compact specimens could be relaxed to $a, b, > 200\text{mm}$ when initiation is defined as $J_{1}\Delta a = 0.2$ from a power law analysis.

Shear lip formation must be reduced (or eliminated) to minimise the small amount of non-conservatism in resistance to crack growth data observed in tests on 10-20mm thick specimens. Such small specimens are required for surveillance monitoring. The desired reduction in shear lips should be achieved by side-grooving which will provide lower bound JG data. Tests on side-grooved specimens have shown that current size requirements for defining size independent JG curves could be relaxed to $b \geq 150\text{mm}$ for $\Delta a \leq 15\% b$.

References


| TABLE I. CHEMICAL COMPOSITION OF THE A533 GRADE 8 CLASS 1 PLATE (wt.%) |
|------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| C                      | Mn             | Si             | Ni             | Cr             | Mo             | Cu             | S              | P              |
| 0.185                  | 1.395          | 0.195          | 0.655          | 0.130          | 0.485          | 0.095          | 0.006          | 0.005          |
| 0.022                  |

| TABLE II. MECHANICAL PROPERTIES (AVERAGE VALUES OVER CENTRAL 100mm OF PLATE) |
|------------------------|----------------|----------------|----------------|----------------|----------------|
| Temp                   | Yield Stress  | UTS (MPa)     | Elongation (%) | Reduction in Area (%) | Onset of Upper Shelf (OC) | Energy (J) @ 20°C | Energy (J) @ 288°C |
| (°C)                   | σy             |               |               |                |                |                  |                  |
| TENSILE (L)            | 444            | 571           | 27            | 72             | 40             | 156              | 230              |
| 288                    | 399            | 545           | 20            | 66             |                |                  |                  |
FIG. 1
INITIATION TOUGHNESS DATA FROM LINEAR JR ANALYSES.

FIG. 2
INITIATION TOUGHNESS DATA FROM POWER LAW ANALYSES

FIG. 3
COMPARISON OF TEARING MODULI FROM DIFFERENT JR CONSTRUCTIONS
FIGURE 4. ASTM E813 Analysis for Valid Results From Non-Side-Grooved Specimens Tested at 288°C.

FIGURE 5. Results for Non-Side-Grooved Specimens Tested at 20°C and Power Law Fit Using Data Where \( \Delta \alpha < 15\% \) b.

FIGURE 6. Results for Side-Grooved Specimens Tested at 20°C. Power Law for All \( \Delta \alpha < 15\% \) b.

FIGURE 7. Results for Non-Side-Grooved Specimens Tested at 288°C. Power Law for All \( \Delta \alpha < 15\% \) b.