Failure Assessment Diagram Analysis of Creep Crack Initiation in 316H Stainless Steel

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Abstract

In this work the time dependent failure assessment diagram (TDFAD) approach is applied to the study of crack initiation in Type 316H stainless steel, a material commonly used in high temperature applications. A TDFAD has been constructed for the steel at a temperature of 550°C, and was found to be relatively insensitive to time. The TDFAD procedure is then applied to predict initiation times, at increments of creep crack growth $\Delta a = 0.2$ mm and $\Delta a = 0.5$ mm, for tests on compact tension specimens and the results compared to experimentally determined values. It has been found that initiation time predictions are sensitive to the creep toughness values, and to the limit load (or reference stress) solution used. Conservative predictions of initiation times have been achieved through the use of the lower bound creep toughness values in conjunction with the plane strain limit load solution. The plane stress limit load solution has given conservative predictions for all bounds of creep toughness used.

Keywords: Failure assessment diagram, creep crack initiation, stainless steel

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1 Introduction

The failure assessment diagram (FAD) approach has been widely used to assess the safety of defects in engineering components, *e.g.* [1]. The time dependent failure assessment diagram (TDFAD), [2], an extended form of the FAD, has recently been developed in order to accommodate the high temperature creep regime within an FAD-based approach. The use of a TDFAD has many advantages—detailed calculations of crack tip parameters such as C^* are not needed; it is not necessary to establish the fracture regime in advance and the TDFAD can indicate whether failure is controlled by crack growth in the small-scale or widespread creep regime or by creep rupture.

The TDFAD procedure is generally used to determine whether a specified crack extension will be achieved within the assessment time. It may also be used to determine the time required for a limited crack extension to occur. Hence approximate initiation times can be obtained, using an engineering definition of initiation, generally taken to be the time for a defined amount of crack extension (typically 0.2 and 0.5 mm), [3]. The procedure is currently limited to cracks under Mode I loading and to the initiation of cracking or crack extensions that are small compared to the defect and component dimensions.

In this work experimental creep crack growth (CCG) test data from [4] for an austenitic Type 316H stainless steel at 550°C, have been analysed. The dependence of the creep toughness K_{mat}^c on time has been determined from these data. TDFADs have been constructed for the material under study and calculations carried out on a selected test to assess the conservatism of the TDFAD approach in the prediction of creep crack initiation. The sensitivity of the creep initiation predictions to the scatter in K_{mat}^c and to the limit load (reference stress) solution used is also examined.

2 Review of the Time Dependent Failure Assessment Diagram (TDFAD) Approach

2.1 TDFAD Parameters

The procedures and parameters used in a TDFAD analysis are similar to that of the R6 Option 2 FAD [1] except that fracture toughness is replaced by creep toughness, to be defined later, and time dependent stress and strain parameters are required. In the TDFAD, for the case of a single primary load, the parameters K_r and L_r are defined as follows:

$$K_r = \frac{K}{K_{mat}^c}, \quad (1)$$

$$L_r = \frac{\sigma_{ref}}{\sigma_{0.2}^c}, \quad (2)$$

In Eq. (1) K is the stress intensity factor and K_{mat}^c is the material creep toughness corresponding to a given crack extension at a given time. In Eq. (2) $\sigma_{0.2}^c$ is the stress corresponding to 0.2% inelastic (creep and plastic) strain from an isochronous stress-strain curve at a particular time and temperature. The definition of $\sigma_{0.2}^c$ is illustrated in Figure 1 and it is seen that $\sigma_{0.2}^c$ will decrease as time increases *i.e.* creep strain increases. The reference stress, σ_{ref} in Eq. (2), may be related to the limit load *via*, $\sigma_{ref} = \frac{P}{P_L} \sigma_0$, where P and P_L are the applied load and the limit load corresponding to a yield stress σ_0 , respectively.

A cut off point $L_r^{\max}$ is also defined on the TDFAD. This is analogous to the $L_r^{\max}$ parameter used in the R6 FAD [1] and is defined as follows:

$$L_r^{\max} = \frac{\sigma_r}{\sigma_{0.2}^c} \quad (3)$$

where σ_r is the stress to cause creep rupture at the same time as $\sigma_{0.2}^c$ is evaluated. If L_r exceeds $L_r^{\max}$, failure is expected to occur by creep rupture rather than by fracture. The creep rupture stress, σ_r in Eq. (3), may be found from experimentally determined relationships between rupture time and stress, such as

$$t_r(\sigma_r) = B \sigma_r^{-\nu}, \quad (4)$$

where t_r is the rupture time for a given rupture stress, and B and ν are material constants. Alternatively, values of σ_r for a range of materials at different times may be obtained directly from design codes [5, 6]. In order to be consistent with the R6 procedure, $L_r^{\max}$ should not exceed $\sigma_f/\sigma_{0.2}$, where $\sigma_{0.2}$ is the 0.2% proof stress and σ_f is the flow stress which may be taken as $(\sigma_{0.2} + \sigma_u)/2$, where σ_u is the ultimate tensile stress.

The evaluation of the material creep toughness parameter, K_{mat}^c , is fundamental to the TDFAD assessment method. Its value at a particular time and crack extension, Δa , is determined from experimental load-displacement data from creep crack growth tests according to the relationship shown below [7],

$$K_{mat}^c = \sqrt{E' J_T}, \quad (5)$$

where $E' = E / (1 - \nu^2)$ and ν is the Poisson's ratio. The total J -integral value, J_T , in Eq. (5) can be evaluated according to the ESIS fracture toughness testing procedure [8], from the total area under the load displacement curve, U_T , as shown in Eq. (6).

$$J_T = \frac{\eta U_T}{B_n (W - a)}, \quad (6)$$

where W is specimen width, a is the crack length, B_n is net specimen thickness (for a side grooved specimen, $B_n = B - B_s$, where B_s is the total sidegroove thickness; for a plane specimen, $B_n = B$) and η is a geometry function, which is equal to $2 + 0.552(1 - a/W)$ for a compact tension specimen. The ESIS procedure is slightly different from that recommended by ASTM E1820 [9]. However calculations have shown that for the cases examined here there is little difference between the results from both procedures.

Typical load-displacement behaviour during a constant load CCG test is shown schematically in Figure 2. The total axial displacement of the loading pins, Δ_T , may be separated into elastic, plastic and creep components Δ_e , Δ_p , Δ_c , respectively. Similarly, the total area under the load displacement curve, U_T , may be separated into elastic, plastic and creep components U_e , U_p , U_c , respectively.

A single test may be used to generate values of K_{mat}^c for a number of values of Δa at a single temperature. However these values will be for different assessment times. A number of different tests, at different load levels, are therefore required to generate the dependence of K_{mat}^c on time for a given Δa , or between K_{mat}^c and Δa for a given time. Creep toughness values, K_{mat}^c , are expected to decrease with time and at short times are expected to approach the low temperature fracture toughness of the material, K_{IC} [10].

2.2 Isochronous Stress-Strain Curves

Isochronous stress-strain curves for the specified temperature are required for each time of interest in order to determine the 0.2% inelastic strain, $\sigma_{0.2}^c$, and the overall TDFAD. The schematic diagram in Figure 1 shows how $\sigma_{0.2}^c$ and $\sigma_{0.2}$ are determined. If sufficient experimental data is not available, theoretical isochronous stress-strain curves can be constructed from the summation of equations which specify the dependence of elastic, plastic and creep strains on stress for the given material and temperature. Isochronous stress-strain curves can also be obtained from design codes [5, 6].

2.3 Formation and Application of TDFAD

A failure assessment diagram for a specific time is defined by the equations:

$$K_r = \left[\frac{E \varepsilon_{ref}}{L_r \sigma_{0.2}^c} + \frac{L_r^3 \sigma_{0.2}^c}{2E \varepsilon_{ref}} \right]^{-1/2} \quad \text{when } L_r \leq L_r^{\max} \quad (7)$$

$$K_r = 0 \quad \text{when } L_r > L_r^{\max}. \quad (8)$$

In Eq. (7) E is Young's modulus and ε_{ref} is the total strain corresponding to the reference stress from the isochronous stress-strain curve at the particular time and temperature (see Figure 1). An example of a TDFAD is shown in Figure 3, which is based on isochronous data for an austenitic steel at 600°C at times of 0, 3000 and 300,000 hours [2].

The TDFAD can be used to predict (i) if a crack will extend a distance Δa in a given time or (ii) the time required for a specified amount of crack extension. Since the engineering definition of creep crack initiation is the period of time required for an increment of crack growth Δa , the TDFAD may be used to predict initiation times. For many materials the curves do not vary greatly with time and curves for longer times can be used to provide a conservative TDFAD for an assessment at shorter times.

The following steps describe the TDFAD assessment procedure [2]:

- (i) Specify component and defect geometry, loading conditions, temperature, *etc.*
- (ii) Define the maximum tolerable crack extension, or if predicting initiation times specify the initiation distance, Δa .

- (iii) Obtain uniaxial creep data for specified times at the operating temperature (*i.e.* σ_r , $\sigma_{0.2}^c$).
- (iv) Construct the TDFAD for each time of interest, using Eq. (7) and the isochronous stress-strain curves.
- (v) Determine values of material creep toughness, K_{mat}^c , for each time of interest for the specified maximum tolerable crack extension / initiation distance, Δa .
- (vi) Calculate values of L_r and K_r at the current value of crack length, a . In initiation time assessments the initial crack length, a_0 , is the appropriate value to use. (The crack extension at initiation $\Delta a \ll a_0$, so that changes in crack size have a negligible effect on these calculations.)
- (vii) Plot the point (L_r , K_r) on the TDFAD. If the point lies within the FAD then the crack extension is less than Δa and creep rupture is avoided in the assessment time. Alternatively, to determine an initiation time, t_i , a time locus of points (L_r , K_r) is constructed, obtained for a single value of crack length, a_0 , at various times. The time for a crack extension Δa is given by the intersection of this locus with the failure assessment curve for the corresponding time.

If the TDFAD is not significantly dependent on time, estimates of initiation times may be made from a curve evaluated at a single time or even from an R6 Option 1 curve. An iterative process can then be implemented in order to refine the estimate, which involves the construction of failure assessment curves for other times [2].

3 Calculation Methodology for Stainless Steel Data

Experimental creep crack growth (CCG) test data from for an austenitic Type 316H stainless steel at 550°C have been analysed (see [4] for full details of the material specification). The material had been taken from an ex-service superheater header removed from a power station that had previously been in service for 76,000 hours at 520°C under a relatively low service load. Data from a total of fourteen creep crack growth tests on compact tension (CT) specimens of three different dimensions, large (L), standard (S) and half-size (HS), (see [4, 11]) have been analysed. Typical dimensions of these specimens are given in Table 1. The specimens were typically side-grooved by 20 or 40 % such that $B_n = 0.8B$ or $B_n = 0.6B$ respectively. Starter cracks had been cut into the specimens using a wire notch eroder.

Constant load tests were carried out at a uniform temperature of 550°C and the applied loads were chosen to give test durations between 500 and 1,500 hours. The amount of crack growth was monitored using a direct current (DC) potential drop technique [3].

3.1 Determination of Initiation Times

The time for 0.2 mm crack extension during the CCG tests of 316H at 550°C has been determined by linearly interpolating between the test times of two consecutively recorded data points where $\Delta a \leq 0.2$ mm and $\Delta a \geq 0.2$ mm respectively. The time to achieve 0.5 mm of crack growth has been determined similarly. The crack extension, Δa , vs. time data for one of these tests on a standard sized specimen is shown in Figure 4, indicating the method used to determine the initiation time for a crack extension of 0.5 mm.

3.2 Evaluating Creep Toughness Values, K_{mat}^c

As discussed in section 2.1, the value of K_{mat}^c is obtained from the area under the load displacement curve up to crack initiation (see Eq. (6)). To determine this area a polynomial equation has been fitted to the load-displacement data during load up of the CCG test, and the integration of this equation gives the area under the loading part of the load displacement curve, ($U_L = U_e + U_p$). A typical polynomial fit is shown in Figure 5 using data from a test on a half size (HS) specimen, which exhibits initial linear behaviour and, at the higher load levels, non-linear behaviour is seen due to plasticity effects. The total area under the load displacement curve at any time, U_T , is then given by the summation of the area under the loading part of the curve (U_L) and the product of the total applied load in the CCG test (which is a constant value) and the increase in axial displacement of the loading pins, *i.e.*

$$U_T = U_L + P\Delta_c \quad (9)$$

Equations (5), (6) and (9) have been employed in order to determine the values of K_{mat}^c for each set of data points measured at specific times during a CCG test. Values of K_{mat}^c for a crack extension Δa , for example $\Delta a = 0.2$ mm, have been determined by linearly interpolating between the values of K_{mat}^c at two consecutively recorded data points where $\Delta a \leq 0.2$ mm and $\Delta a \geq 0.2$ mm, respectively.

3.3 Reference Stress Solutions

When calculating L_r , a reference stress solution, representing either plane strain (PE) or plane stress (PS) conditions may be used. A general definition of the reference stress solution for a CT specimen may be described by:

$$\sigma_{ref} = \frac{P}{mB_{eff}W}, \quad (10)$$

where P is the load applied to the specimen, W is the specimen width, m is a geometric function which varies under conditions of plane stress and plane strain, and B_{eff} is the effective thickness of the specimen which is determined from [12]

$$B_{eff} = B_n \left(2 - \frac{B_n}{B} \right), \quad (11)$$

The value of m for the CT specimen using the von Mises solution is [13],

$$m = \lambda \left[- \left(1 + \gamma \frac{a}{W} \right) + \sqrt{(1 + \gamma) \left\{ 1 + \gamma \left(\frac{a}{W} \right)^2 \right\}} \right], \quad (12)$$

$$\text{where, } \lambda = \begin{cases} 1 \\ 2/\sqrt{3} \end{cases} ; \gamma = \begin{cases} 2/\sqrt{3} & \text{plane stress} \\ 1 & \text{plane strain} \end{cases}$$

For a given a/W the value of m is lower under plane stress conditions than plane strain, resulting in higher values of L_r in plane stress for the same applied load, (for a typical CT specimen examined here the plane stress reference stress is about 45% higher than the plane strain value). Assessments made using the plane stress solution will thus generally give a more conservative result than that obtained using the plane strain solution.

3.4 Time Dependent Stress-Strain Data

Isochronous stress-strain data have been generated using the elastic, elastic-plastic and creep material response. The method used follows the procedure in the RCC-MR design code [14] for primary-secondary creep of Type 316 stainless steel material. Thus, the primary and secondary creep strain increments, $\Delta \varepsilon_p^c$ and $\Delta \varepsilon_s^c$, are calculated according to:

$$\Delta \varepsilon_p^c = p A_p^{1/p} \sigma^{n_p/p} \varepsilon^{(1-1/p)} \Delta t, \quad (13)$$

$$\Delta \varepsilon_s^c = A \sigma^n \Delta t.$$

The creep strain increment, $\Delta \varepsilon^c$, is equal to the larger of the two increments calculated from Eq. (13) *i.e.*

$$\Delta \varepsilon^c = \begin{cases} \Delta \varepsilon_p^c & \text{for } \Delta \varepsilon_p^c \geq \Delta \varepsilon_s^c \\ \Delta \varepsilon_s^c & \text{for } \Delta \varepsilon_p^c < \Delta \varepsilon_s^c \end{cases} \quad (14)$$

The primary and secondary creep constants in Eq. (13) are $p = 0.746$, $A_p = 2.60 \times 10^{-23}$, $n_p = 7.45$, $A = 1.559 \times 10^{-35}$ and $n = 11.95$ (for stress in MPa), which were obtained by fitting to uniaxial creep data over a range of conditions [4].

For a particular time, the total strain at any stress level is given by the sum of the elastic and plastic strain and the total creep strain accumulated in that time:

$$\varepsilon^{total}(\sigma, t) = \varepsilon^e(\sigma) + \varepsilon^{pl}(\sigma) + \sum_t \Delta \varepsilon^c(\sigma, \Delta t). \quad (15)$$

There were insufficient tensile data in [4] which could be used to provide the elastic-plastic response of the material in Eq. (15). Therefore data were obtained from material of the same cast, which had been exposed to similar, but not identical, service conditions to that of the test specimens analysed here [4].

Isochronous stress strain curves based on Eqs. (13) to (15) have been produced for the times listed in Table 2, examples of which are shown in Figure 6. It may be seen that the isochronous stress strain curves are relatively independent of time for times below 1000 hrs. Values of the 0.2% stress, $\sigma_{0.2}^c$, taken from these curves together with values of rupture stress are given in Table 2.

Regression analysis of rupture time vs. stress, from the uniaxial creep data in [4], provided the values of the constants in the creep rupture equation, Eq. (4), as $B = 9.57 \times 10^{31}$ and $\nu = 1.41$, with stress in MPa and time in hours. Thus Eq. (4) in conjunction with Eq. (3) can be used to determine $L_r^{\max}$ at different times.

4 Results

4.1 Creep Toughness

4.1.1 Variation of Creep Toughness with Time and Data Bounds of K_{mat}^c

The creep toughness data from each test have been combined to determine the relationship between K_{mat}^c and time at temperature, $T = 550^\circ\text{C}$ and crack extensions of $\Delta a = 0.2$ mm and $\Delta a = 0.5$ mm as illustrated in Figure 7 and Figure 8, respectively. Different symbols have been used in the figures to illustrate the data for the different specimen size, although no obvious trend with specimen size is observed. A mean trend line was fitted to the K_{mat}^c data as shown in Figure 7 and Figure 8.

If the creep toughness is assumed to follow a normal distribution, then upper and lower bound K_{mat}^c values can be determined by offsetting the mean line in Figure 7 and Figure 8 to the data by ± 2 standard deviations (s.d.). These data bounds are shown in Figure 7 and Figure 8. By comparing Figure 7 and Figure 8 it may be seen that defining initiation at $\Delta a = 0.2$ mm will lead to a lower value of K_{mat}^c , with a somewhat higher associated scatter, compared to that obtained using $\Delta a = 0.5$ mm. It is also apparent that the creep toughness is high, and not significantly reduced by creep in the timescales of these tests.

4.1.2 Sensitivity of Creep Toughness to the Area under the Loading Curve

Typical experimental load-displacement curves from the tests on CT specimens are illustrated in Figure 9 up to $\Delta a = 0.5\text{mm}$, where the load, P , has been normalised by the width, W , and thickness, B , of these (plane sided) specimens, and the Young's modulus of the material, E . The displacement here, which has been normalised into non-dimensional form by the specimen width, W , is the total axial displacement that includes the elastic, plastic and creep displacements. Note that the linear portion of the curve for the large and half size specimens (L and HS in Figure 9, respectively) should lie very close to each other when plotted in this normalised form, since the specimens are geometrically similar ($a/W = 0.45$, $B/W \approx 0.5$ in both cases). The measured stiffness during load-up of the large specimen is very close to the theoretical value from [9], but the half size specimens exhibits a larger displacement. This is likely to be due to experimental error and suggests that the elastic area in Figure 2 would be better estimated from stress intensity factor solutions than from measured elastic displacement, as in some J -estimation methods [9]. However, the measured variability in the

loading curve for the HS specimen produces variability in creep toughness that is well within the upper and lower bound toughness lines for K_{mat}^c in Figure 7.

It is seen in Figure 9 that for all the specimens, particularly the large CT specimen, a significant proportion of the area under the loading curve corresponds to the elastic and plastic area, *i.e.* creep initiation at these times is dominated by the elastic plastic response. The evaluation of the area under the load up part of the curve can therefore be of significance when calculating K_{mat}^c at short incubation times. This trend is illustrated more clearly in Figure 10 where the ratio of the area under the loading part of the curve to the total area under the curve, U_L / U_T is shown for the three specimen sizes. In the case of the large specimen, the area under the load up part of the curve is about 90% of the total area under the load displacement curve at the defined initiation increments ($\Delta a = 0.2, 0.5$ mm).

4.2 TDFAD for 316 H at 550°C

Time dependent failure assessment diagrams, for the times listed in Table 2, have been produced for this material at 550°C. The R6 Option 1 FAD [1], which is applicable at low temperatures has also been determined. These diagrams are shown in Figure 11 and Figure 12, respectively. At times of 100 hrs and below, the value of $L_r^{\max}$ given by Eq. (3), exceeds that obtained from an R6 analysis. $L_r^{\max}$ would therefore be set equal to the value given by the R6 procedure as discussed in Section 2.

The TDFAD at time zero is compared to the R6 Option 1 curve in Figure 11. Both curves lie close to each other especially at lower values of L_r . Figure 12 shows the evolution of the TDFAD up to a time of 100,000 hours. It is observed that the TDFAD is quite insensitive to time and the greatest noticeable difference between the diagrams at each time is the cut off value, $L_r^{\max}$, which decreases as time increases, indicating the reduction of time to failure by continuum damage, due to the reduction in σ_f with increasing time *via* Eq. (4). The insensitivity of the curves in Figure 12 to time is due to the high value of creep stress exponent, n , in the creep strain equation (see Eq. (13)) which may not be valid at the longer times.

5 Application of TDFAD to Predict Initiation Times

An example of the use of a TDFAD to predict initiation times is presented as an illustration of the application of the method. The initiation time of a test on a standard sized CT

specimen ($P = 23.5$ kN, $a/W = 0.53$, $B/W = 0.5$, $B_n/W = 0.4$), has been predicted and compared to the experimentally determined value. This test has not been used to produce a value of K_{mat}^c at initiation since not all of the necessary data required were available for this test. The sensitivity of the initiation time prediction to the variability in the creep toughness data and to the reference stress solution used have also been investigated.

A locus of data points at times of 10, 100, 500, and 1000 hours has been constructed on a TDFAD for this test. Figure 13 and Figure 14 focus on the parts of the TDFAD where the loci are close to the curve when the plane strain and plane stress limit load solutions are used, respectively. The point on any single locus with the lowest L_r or K_r value corresponds to the lowest time of 10 hrs; subsequent points on the locus correspond to the increasing times 100, 500 and 1000 hrs. A TDFAD curve for a time of 100 hrs has been used in the analysis since it is already known that the initiation times are in the range of 0 to 500 hrs for these tests, and little difference has been observed (Section 4.2) between the TDFADs in this time range. Note that the small increase in L_r , in Figure 13 and Figure 14, is due to a reduction in $\sigma_{0.2}^c$ with time and the increase in K_r is due to the decrease in K_{mat}^c with time. Three loci are shown in Figure 13 and Figure 14, a lower bound (LB), mean and upper bound (UB) locus, for both initiation distances $\Delta a = 0.2$ and 0.5 mm, which were produced using the lower bound, mean and upper bound values of K_{mat}^c determined from Figure 7 and Figure 8.

As explained in Section 2.3, initiation is deemed to occur at a time corresponding to the point where the locus intersects the TDFAD curve. It may be seen in Figure 13 that when the plane strain reference stress value is used, the predicted initiation time corresponding to $\Delta a = 0.5$ mm is greater than 1000 hrs except when the lower bound toughness value is used (labelled as LB Locus $\Delta a = 0.5$ mm in Figure 13) when the initiation time is approximately 100 hrs. (Values of K_{mat}^c (and hence prediction loci) have not been extrapolated beyond 1000 hrs since there may be a change in the trend of the data for longer term tests [15]). The measured initiation time corresponding to $\Delta a = 0.5$ mm for this test was 275 hours thus a conservative prediction is achieved through the use of the lower bound K_{mat}^c data. For $\Delta a = 0.2$ mm, the TDFAD analysis using the lower bound toughness predicts that the initiation time is approximately 10 hrs, which is conservative compared to a measured time of 105 hrs (see Table 3).

If the plane stress reference stress definition is used, as illustrated in Figure 14, it may be seen that the initiation time for the specimen (for $\Delta a = 0.2$ or 0.5 mm) is less than 100 hrs regardless of whether the lower, mean or upper bound value is used for the creep toughness, K_{mat}^c . This illustrates the strong dependence of the result on the choice of reference stress solution.

The initiation times predicted by this method using the loci corresponding to mean, upper bound (UB) and lower bound (LB) values of K_{mat}^c and the plane stress and plane strain von Mises limit load solutions are compared to the experimentally determined initiation times in Table 3. Although this side-grooved, standard-sized test specimen may be expected to be represented more closely by the plane strain solution than plane stress, the initiation times predicted by a plane strain analysis are not conservative, unless the lower bound creep toughness is used.

A direct comparison is made in Figure 15 of the results obtained using the plane strain or the more conservative plane stress von Mises reference stress solution for $\Delta a = 0.5$ mm. On this scale the prediction loci are close to being vertical since, as can be seen in Table 2, $\sigma_{0.2}^c$ is approximately constant over the timescale considered, and the only significant change is in K_{mat}^c . The shift in the data due to the use of the different reference stress solutions is clearly observed. For this specimen the plane stress solution gives an L_r value 1.44 times greater than that from the plane strain solution (see Eq. (11)) and the effects on the predicted initiation times are significant.

The sensitivity to the reference stress solution will depend on the region of the TDFAD in which the prediction loci are situated. For this material and temperature the failure assessment curve is approximately horizontal for values of L_r greater than 1.7. Thus, a horizontal shift to the locus, due to the use of a different reference stress solution, will have very little effect on initiation time predictions in the region $L_r > 1.7$. Similarly if the loci fall in the region, $L_r < 0.5$, the results will not be very sensitive to the choice of reference stress solution. However, as illustrated above, if the loci fall in the region, $0.5 < L_r < 1.4$ the predicted initiation times can decrease by up to two orders of magnitude when the reference stress increases by less than 50 percent.

6 Conclusions

Creep toughness values, K_{mat}^c , have been determined for austenitic Type 316H stainless steel at 550°C from analysis of fourteen creep crack growth tests on CT specimens of different sizes and thickness. Values of K_{mat}^c were obtained for two initiation distances, $\Delta a = 0.2$ mm and $\Delta a = 0.5$ mm. It has been found that for the 316 steel at 550°C the area under the loading part of the curve in a creep crack growth (CCG) test, which is used to determine K_{mat}^c , cannot be neglected. Accurate data from the load-up part of a CCG test are therefore essential in determining accurate values of K_{mat}^c . Time dependent failure assessment diagrams (TDFAD) have been produced at various assessment times and the shape of the curve is found to be insensitive to time. Initiation times have been predicted using the TDFAD approach and the lower bound, mean and upper bound K_{mat}^c values, with both the plane stress and plane strain reference stress solution used in the calculation of L_r . When the plane strain reference stress solution is used conservative predictions have been obtained only through the use of the lower bound K_{mat}^c values. However, the plane stress solution has resulted in conservative predictions when used with all bounds of K_{mat}^c .

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Specimen Size	Width W (mm)	Thickness B (mm)	Net Thickness B_n (mm)
Large (L)	104	50	50
Standard (S)	50	25	25
Half size (HS)	26	13	13

Table 1: Typical dimensions of compact tension specimens used in the analysis.

Time (hrs)	$\sigma_{0.2}^c$ (MPa)	σ_r (MPa)
0	175	—
100	175	425
500	174	369
1000	173	347
10000	164	284
100000	143	232

Table 2: Rupture stress and stress corresponding to 0.2% inelastic strain at specific times.

Limit Load Solution	$t_i (\Delta a = 0.2 \text{ mm}) \text{ (hrs)}$				$t_i (\Delta a = 0.5 \text{ mm}) \text{ (hrs)}$			
	Exp	UB	Mean	LB	Exp	UB	Mean	LB
Plane Strain (PE)	105	> 1000	> 1000	≈ 10	275	> 1000	> 1000	≈ 100
Plane Stress (PS)	105	< 100	< 10	< 10	275	< 10	< 10	< 10

Table 3: Comparison of experimentally determined initiation times (Exp) and TDFAD predictions using upper bound (UB), mean and lower bound (LB) K_{mat}^c data.

Figure 1: Schematic isochronous stress strain curve, after [10] indicating the definition of $\sigma_{0.2}^c$ and σ_{ref} .

Figure 2: Schematic load-displacement behaviour in a creep crack growth test, after [10].

Figure 3: Schematic example of a time dependent failure assessment diagram (TDFAD) based on data from an austenitic steel [2].

Figure 4: Determination of initiation time, t_i , for $\Delta a = 0.5$ mm from experimental data [4].

Figure 5: Load, P , vs. displacement, Δ , data during load up in a test on a HS specimen.

Figure 6: Isochronous stress-strain curves generated for 316H stainless steel at 550°C

Figure 7: Data bounds for the fracture toughness, K^c_{mat} , for Type 316 Material at 550° C ($\Delta a = 0.2$ mm).

Figure 8: Data bounds for the fracture toughness, K^c_{mat} , for Type 316 Material at 550° C ($\Delta a = 0.5$ mm).

Figure 9: Typical normalised load-displacement curve for Large (L), Standard (S) and Half Size (HS) CT specimens in a CCG tests (up to $\Delta a = 0.5$ mm).

Figure 10: Comparison of the ratio of the loading area, U_L , to total area under, U_T , the load displacement curve, as crack extension proceeds, for a Large (L), Standard (S) and Half Size (HS) CT specimen.

Figure 11: TDFAD at time $t = 0$ hours and R6 Option 1 FAD.

Figure 12: TDFAD for austenitic Type 316H stainless steel over a range of times.

Figure 13: Application of a TDFAD to predict initiation times of a test using the plane strain limit load solution.

Figure 14: Application of a TDFAD to predict initiation times of a test using the plane stress limit load solution.

Figure 15: Comparison of predictions at $\Delta a = 0.5$ mm, using plane stress (PS) and plane strain (PE) limit load solutions. (Points on prediction loci are at times of 10, 100, 500 and 1000 hours).