

Comparison of procedures for the assessment of creep crack initiation

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ABSTRACT

In large components, such as rotors and steam pipework, defects due to manufacturing processes have to be taken into account and creep crack initiation and growth assessments for these defects may be required. In many cases, the initiation period will occupy a significant proportion, if not all, of the assessment period being considered. The Time Dependent Failure Assessment Diagram (TDFAD) approach is currently being developed within the R5 procedures as an alternative to conventional methods for predicting initiation and the early stages of creep crack growth. A similar Two Criteria Diagram approach has been developed independently in Germany to assess creep crack initiation in ferritic steels. Both approaches are being investigated in a study being carried out within the Thematic Network "Advanced Creep" (ECCC) Working Group 1.2 on "Creep Crack Initiation". This paper first describes the two approaches and then presents a comparison of their application to the prediction of initiation in creep crack growth tests conducted on Compact Tension (CT) specimens manufactured from a ferritic 1CrMoV steel and an austenitic Type 316H steel.

1. INTRODUCTION

In large components, such as rotors and steam pipework, defects due to manufacturing processes have to be taken into account and creep crack initiation and growth assessments for these defects may be required. In many cases, the initiation period will occupy a significant proportion, if not all, of the assessment period being considered.

Conventional methods for assessing initiation and the early stages of creep crack growth are generally based on the evaluation of parameters including crack opening displacement, δ , and crack tip parameters C^* and $C(t)$ together with experimental data describing creep crack initiation or growth [1]. However, for low temperature fracture, the simplified R6 procedure [2] has been developed, which uses the concept of a Failure Assessment Diagram (FAD) to avoid detailed calculations of crack tip parameters. In recent years, FAD approaches have been extended to the creep regime [3-6] and the high temperature Time Dependent Failure Assessment Diagram (TDFAD) method has now been formally incorporated into the R5 high temperature assessment procedure [7]. A key requirement of TDFAD approaches is the evaluation of a time dependent creep toughness, denoted K_{mat}^c , and a number of methods for defining this parameter have been proposed [8-9].

In Germany, a similar Two Criteria Diagram (2CD) Approach has been independently developed to assess creep crack initiation in ferritic steels [10-12]. This approach uses crack tip and ligament damage parameters, R_K and R_σ , respectively, which are similar to the parameters K_r and L_r used in the R5 TDFAD. The critical stress intensity factor, K_{Iid} , is used

as a measure of crack initiation resistance rather than the creep toughness, K_{mat}^c , used in the R5 approach.

Within the Thematic Network “Advanced Creep”, Working Group 1.2 was established in order to make a contribution to advanced creep assessment by making recommendations for the determination and use of creep crack initiation data. As part of this process, the following topics are being considered:

- A review and discussion of testing practices
- Evaluation of tests and data assessment procedures
- Use of data for component assessment
- Establishing a platform for data review and collation
- Comparison of creep crack initiation assessment procedures, with particular emphasis on the R5 TDFAD and Two Criteria Diagram (2CD) approaches

This paper first describes the R5 TDFAD and Two Criteria Diagram (2CD) approaches and then presents selected results from comparisons of their application to the prediction of initiation in creep crack growth tests conducted on Compact Tension (CT) specimens manufactured from a ferritic 1CrMoV steel [13] and an austenitic Type 316H steel [14].

2. CREEP CRACK INITIATION ASSESSMENT PROCEDURES

2.1 R5 TDFAD Approach

The TDFAD is based on the Option 2 FAD specified in R6 [2] and involves a failure assessment curve relating the two parameters K_r and L_r , which are defined in equations (1) and (2) below, and a cut-off L_r^{max} . For the simplest case of a single primary load acting alone

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

where K is the stress intensity factor and K_{mat}^c is the creep toughness, and

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

where σ_{ref} is the reference stress and $\sigma_{0.2}^c$ is the stress corresponding to 0.2% inelastic (plastic plus creep) strain from the average isochronous stress-strain curve for the temperature and assessment time of interest, see Figure 1. The failure assessment diagram is then defined by the equations

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

$$K_r = 0 \quad L_r > L_r^{max} \quad (4)$$

In equation (3), E is Young's modulus and ϵ_{ref} is the total strain from the average isochronous stress-strain curve at the reference stress, $\sigma_{ref} = L_r \sigma_{0.2}^c$, for the appropriate time and temperature. Thus, equation (3) enables the TDFAD to be plotted with K_r as a function of L_r , as shown schematically in Figure 2. The cut-off, L_r^{max} , is defined as

$$L_r^{max} = \text{Min}[\sigma_R / \sigma_{0.2}^c, \bar{\sigma} / \sigma_{0.2}] \quad (5)$$

where σ_R is the rupture stress for the time and temperature of interest, $\bar{\sigma}$ is the short-term flow stress and $\sigma_{0.2}$ is the conventional 0.2% proof stress. The first term on the right hand

side of equation (5) ensures that creep rupture of the remaining ligament is precluded and the second term corresponds to the R6 [2] L_r^{\max} parameter given by $\bar{\sigma}/\sigma_{0.2}$. As in R6 [2], $\bar{\sigma}$ may be taken as $(\sigma_{0.2} + \sigma_u)/2$ where σ_u is the ultimate tensile strength.

A central feature of the TDFAD approach is the definition of an appropriate creep toughness which, when used in conjunction with the failure assessment diagram, ensures that creep crack growth in the assessment period is less than a value Δa . Creep toughness values may be estimated indirectly from conventional creep crack initiation and growth data or evaluated directly from experimental load versus displacement information [9]. The latter direct approach for evaluating creep toughness values is described below.

Creep toughness can be determined from experimental load-displacement data by using methods developed to derive critical values of the J-integral and hence the material toughness, K_{mat} , given in low temperature fracture toughness testing standards [15-17]. Consider a load-controlled creep crack growth test conducted on a standard compact tension (CT) specimen resulting in a typical load-displacement trace of the form shown in Figure 3. If it is assumed that the amount of crack growth in the test, Δa , is small, the total displacement, Δ_T , may be conveniently partitioned into elastic, plastic and creep components, denoted Δ_e , Δ_p and Δ_c , respectively, where

$$\Delta_T = \Delta_e + \Delta_p + \Delta_c \quad (6)$$

Similarly, the total area under the load-displacement curve, U_T , may be conveniently partitioned into elastic, plastic and creep components, denoted U_e , U_p and U_c , respectively, where

$$U_T = U_e + U_p + U_c \quad (7)$$

Whilst the ESIS fracture toughness testing procedure [15] evaluates experimental total J values, J_T , by using the total area under the load-displacement curve¹, U_T , the British Standard [16] and ASTM [17] testing procedures evaluate the elastic contribution to J as K^2/E' instead of using the elastic area, U_e . Values of creep toughness, K_{mat}^c , may then be derived from creep crack growth tests as a function of crack growth increment, Δa , using

$$K_{\text{mat}}^c = \sqrt{E'J_T} \quad (8)$$

in conjunction with the experimental total J value, J_T .

It is considered that the British Standard [16] and ASTM [17] approaches for deriving the elastic contribution to J based on K^2/E' are more robust than the ESIS approach. This is because the ESIS approach uses U_e to derive the elastic contribution to J, which implicitly assumes that the initial portion of the load-displacement curve accurately reflects the elastic compliance of the specimen². The following expression for direct evaluation of creep toughness from experimental load-displacement information has therefore been proposed

¹ Noting that fracture toughness testing procedures do not include U_c , the creep contribution to the total area under the load-displacement curve.

² Noting that the initial slope of the load-displacement curve is likely to be influenced by other factors.

$$K_{\text{mat}}^c = \left[K^2 + \frac{E'\eta}{B_n(w-a_0)} \left(U_p + \frac{n}{n+1} U_c \right) \right]^{1/2} \quad (9)$$

where n is the creep stress exponent and the factor $n/(n+1)$ is required for consistency with standard creep crack growth testing procedures [18] as U_c is defined here as

$$U_c = P\Delta_c \quad (10)$$

where P is the applied load. Therefore equation (10) can alternatively be expressed as

$$K_{\text{mat}}^c = \left[K^2 + \frac{E'\eta U_p}{B_n(w-a_0)} + \frac{n}{n+1} \frac{E'\eta P\Delta_c}{B_n(w-a_0)} \right]^{1/2} \quad (11)$$

which only differs from the equation (A5.4) of Appendix A5 of R5 Volume 4/5 [7] in the use of $E' = E/(1-\nu^2)$ rather than E and the inclusion of an additional second term in equation (11) to incorporate the effects of plasticity during loading. Creep toughness values for a given material are dependent on the crack growth increment, Δa , and time; K_{mat}^c values reduce with reducing Δa and increasing time.

2.2 Two Criteria Diagram Approach

The Two Criteria Diagram is shown in Figure 4. Here, the failure assessment curve is described by two parameters, R_K and R_σ , which are defined in equations (12) and (13), respectively. The crack tip damage parameter, R_K , is defined as

$$R_K = K / K_{\text{lid}} \quad (12)$$

where K is the stress intensity factor and K_{lid} is the critical value of K at creep crack initiation. The ligament damage parameter, R_σ , is defined as

$$R_\sigma = \sigma_{\text{npl}} / \sigma_R \quad (13)$$

where σ_{npl} is the nominal stress, given for a CT specimen by [12]:

$$\sigma_{\text{npl}} = \frac{P}{\sqrt{B_n B(w-a)}} \left\{ 1 + 2 \left[\frac{(w+a)}{(w-a)} \right] \right\} \quad (14)$$

and σ_R is the rupture strength for the time and temperature of interest.

The Two Criteria Diagram considered in this comparison is shown in Figure 4; this is restricted to materials with sufficiently high creep deformation capability which do not exhibit notch weakening (creep brittle) behaviour³. The FAD is separated into three regions by the value of the ratio R_σ / R_K , as follows: ligament damage for $R_\sigma / R_K \geq 2$; crack tip damage for $R_\sigma / R_K \leq 0.5$; and mixed damage for $0.5 < R_\sigma / R_K < 2$.

The critical value of K at creep crack initiation, K_{lid} , is determined from creep crack growth tests on 50 mm (width) CT specimens; K_{lid} values reduce with reducing Δa and increasing time.

³ An alternative FAD has been proposed for notch weakening (creep brittle) materials [12] although this diagram is not considered further in this paper.

3. COMPARISON OF R5, TDFAD AND TWO CRITERIA DIAGRAM PARAMETERS

In this section, the R5 TDFAD and Two Criteria Diagram are compared for 1CrMoV and Type 316H steels at 550°C using creep crack initiation data (based on a crack growth increment, $\Delta a = 0.2$ mm) from 20% sidegrooved CT specimens. It should be noted that whilst the creep crack initiation data for Type 316H steel [14] were obtained from individual 38 mm (width) CT specimens, the data for 1CMV steel were derived from best fits to the crack growth and displacement behaviour of a number of identical 50 mm CT specimens tested under the same conditions [13]. In addition, EDM starter cracks were used in all of the 1CrMoV tests, whereas all of the Type 316H tests used specimens containing fatigue pre-cracks.

3.1 Comparison of Assessment Parameters

A comparison can be made between the assessment parameters in the TDFAD and 2CD approaches. L_r can be compared with R_σ and K_r can be compared with R_K . First the ligament parameters, L_r and R_σ , are compared:

$$L_r = \sigma_{\text{ref}} / \sigma_{0.2}^c \quad (15)$$

$$R_\sigma = \sigma_{\text{npl}} / \sigma_R \quad (16)$$

The first noticeable difference is that L_r lies on the abscissa of the R5 TDFAD and R_σ lies on the ordinate of the Two Criteria Diagram. The reference stress, σ_{ref} , can be compared with the nominal stress, σ_{npl} . The reference stress can be defined for the appropriate stress state (plane stress or plane strain) and either Tresca or von Mises yield surfaces. Two cases have been considered here:

- (a) Plane stress Tresca; this results in values of reference stress which are closest to the nominal stress, σ_{npl} .
- (b) Plane strain von Mises; this may be more appropriate when analysing experimental data from sidegrooved CT specimens.

Non-dimensional values of reference stress for these two cases are given below.

Based on plane stress Tresca [2]:

$$\sigma_{\text{ref}} \cdot \frac{B_n(w-a)}{P} = \frac{(1-a/w)}{\left(2 + 2(a/w)^2\right)^{1/2} - 1 - (a/w)} \quad (17)$$

Based on plane strain von Mises [2]:

$$\sigma_{\text{ref}} \cdot \frac{B_n(w-a)}{P} = \frac{(\sqrt{3}/2)(1-a/w)}{\left(2.702 + 4.599(a/w)^2\right)^{1/2} - 1 - 1.702(a/w)} \quad (18)$$

Similarly, the nominal stress from equation (14) can be expressed non-dimensionally as:

$$\sigma_{n,pl} \cdot \frac{B_n(w-a)}{P} = \sqrt{\frac{B_n}{B}} \left\{ 1 + 2 \left[\frac{(w+a)}{(w-a)} \right] \right\} \quad (19)$$

The plane stress Tresca and plane strain von Mises reference stresses are compared with the nominal stress in Figure 5(a) and associated values of the ratio $\sigma_{ref} / \sigma_{n,pl}$ are shown in Figure 5(b), for the value of $B_n/B = 0.8$ appropriate to the side-grooved 1CrMoV and 316H CT specimens.

The stress corresponding to 0.2% inelastic (plastic plus creep) strain, $\sigma_{0.2}^c$ (0.2% inelastic strength), can also be compared with the rupture strength, σ_R ; this comparison is described in Section 4.2.

The crack tip parameters, K_r and R_K , can also be compared:

$$K_r = K / K_{mat}^c \quad (20)$$

$$R_K = K / K_{lid} \quad (21)$$

K_r lies on the ordinate of the R5 TDFAD and R_K lies on the abscissa of the Two Criteria Diagram. The numerator in both parameters is the stress intensity factor, K . The material initiation parameters, K_{mat}^c and K_{lid} , are compared in Section 4.2.

3.2 Comparison of Material Parameters

The parameter $\sigma_{0.2}^c$ in the R5 TDFAD approach is the stress to give 0.2% inelastic (plastic plus creep) strain at the assessment time, denoted the 0.2% inelastic strength. The variations of $\sigma_{0.2}^c$ and the rupture stress, σ_R , with time for 1CrMoV steel at 550°C are shown in Figure 6(a). For completeness, this figure also shows the variation in the stress to give 1% inelastic strain, $\sigma_{1.0}^c$. Figure 6(b) shows the 0.2% and 1% inelastic strength values normalised by the rupture stress, σ_R . Similar plots for Type 316H steel at 550°C are shown in Figures 7(a) and 7(b). The inelastic strength values for 1CrMoV steel at 550°C shown in Figure 6 for times in excess of 100 hours are dominated by creep effects as plastic strains are negligible at these stress levels; in this case inelastic and creep strength values are almost identical. However, Figure 7 shows that inelastic and creep strength values for Type 316H steel at 550°C only become identical at very long times ($\sim 10^5$ hours).

The creep toughness parameter, K_{mat}^c , can also be compared with the critical stress intensity factor, K_{lid} . Figures 8 and 9 show these comparisons for 1CrMoV and Type 316H steels, respectively, at 550°C. These figures show that for Type 316H steel, the ratio K_{mat}^c / K_{lid} tends to unity at long times, whereas K_{mat}^c values for 1CrMoV steel remain significantly larger than K_{lid} values for all test durations.

3.3 Overall Comparison

In this Section the R5 TDFAD and Two Criteria Diagram are compared. In order to compare the FADs from the two approaches it is necessary to transform R_σ to L_r and R_K to K_r using the following equations.

$$L_r = \frac{\sigma_{\text{ref}}}{\sigma_{0.2}^c} = R_\sigma \left[\frac{\sigma_R}{\sigma_{0.2}^c} \cdot \frac{\sigma_{\text{ref}}}{\sigma_{\text{npl}}} \right] \quad (22)$$

and

$$K_r = \frac{K}{K_{\text{mat}}^c} = R_K \left[\frac{K_{\text{lid}}}{K_{\text{mat}}^c} \right] \quad (23)$$

These equations allow the Two Criteria FAD to be plotted on the R5 TDFAD in (L_r, K_r) space and the R5 TDFAD to be plotted on Two Criteria Diagram in (R_K, R_σ) space. The comparison for 1CrMoV steel is first presented in Figure 10 in (L_r, K_r) space. The (L_r, K_r) points obtained at the experimentally measured initiation times have been plotted in Figures 10(a) and 10(b) using plane stress Tresca and plane strain von Mises reference stress solutions, respectively. The test data are plotted at the measured initiation times using appropriate values of $\sigma_{0.2}^c$ and σ_R (from Figure 6(a)) and K_{mat}^c and K_{lid} (from the lines fitted to the data in Figure 8). Figures 11(a) and 11(b) then show comparisons of the two approaches for 1CrMoV steel in (R_K, R_σ) space. Similar comparisons for Type 316H steel are then shown in Figures 12 and 13; in this case values of $\sigma_{0.2}^c$ and σ_R are taken from Figure 7(a) and K_{mat}^c and K_{lid} are taken from the lines fitted to the data in Figure 9. In all of these figures, the failure assessment curves are only shown for the shortest and longest experimental initiation times; curves for intermediate times would lie between these two extremes.

The relative positions of the R5 TDFAD and Two Criteria Diagram are sensitive to time through the time dependence of the $\sigma_R / \sigma_{0.2}^c$ and $K_{\text{lid}} / K_{\text{mat}}^c$ ratios, which in turn influence the ratios between the assessment parameters L_r / R_σ and K_r / R_K . The ratio L_r / R_σ is also sensitive to the assumed reference stress solution and hence the value of the ratio $\sigma_{\text{ref}} / \sigma_{\text{npl}}$. Figures 10-13 show that the R5 TDFAD for 1CrMoV steel at 550°C is significantly more sensitive to time than for Type 316H steel at the same temperature; this results from isochronous stress-strain curves for 1CrMoV steel at 550°C being more sensitive to time than those for Type 316H steel at the same temperature.

The Two Criteria Diagram approach gives conservative predictions of creep crack initiation in 1CrMoV and Type 316H CT specimens tested at 550°C, with the level of conservatism reducing with increasing test duration. The R5 TDFAD approach also gives conservative initiation predictions for both materials based on a plane stress Tresca reference stress and best estimate materials data (Figures 10(a) and 12(a)). For Type 316H steel, conservative, but more accurate, initiation predictions are also obtained using the R5 TDFAD approach based on a plane strain von Mises reference stress and best estimate materials data. However, for 1CrMoV steel, slightly non-conservative initiation predictions are obtained using the R5 TDFAD approach based on a plane strain von Mises reference stress. A preliminary consideration of the deformation behaviour of the CT specimens for the two materials suggests that for Type 316H steel, the experimental load-line displacements are consistent with predictions based on a plane strain von Mises reference stress, whereas for 1CrMoV steel, the experimental load-line displacements are more consistent with predictions based on

a plane stress Tresca reference stress. Further work is required to understand the differences in behaviour observed for these two materials.

4. CONCLUDING REMARKS

A comparison of R5 TDFAD and Two Criteria Diagram approaches for predicting creep crack initiation has been carried out using available materials data for 1CrMoV and Type 316H steels at 550°C. It has been shown that the R5 TDFAD for 1CrMoV steel at 550°C is significantly more sensitive to time than for Type 316H steel at the same temperature. The Two Criteria Diagram approach gives conservative predictions of creep crack initiation in both materials. The R5 TDFAD approach also gives conservative initiation predictions for both materials based on a plane stress Tresca reference stress. For Type 316H steel, conservative, but more accurate, initiation predictions are also obtained using the R5 TDFAD approach based on a plane strain von Mises reference stress. However, for 1CrMoV steel, slightly non-conservative initiation predictions are obtained using the R5 TDFAD approach based on a plane strain von Mises reference stress. Further work is required to understand the differences in behaviour observed for these two materials.

REFERENCES

1. G A Webster and R A Ainsworth, High Temperature Component Life Assessment, Chapman and Hall, London, 1994.
2. R6 Revision 4, Assessment of the Integrity of Structures Containing Defects, British Energy Generation Ltd. Procedure, 2001.
3. R A Ainsworth, The Use of a Failure Assessment Diagram for Initiation and Propagation of Defects at High Temperatures, Fatigue Fract. Engng. Mater. Struct., **16**, 1091-1108, 1993.
4. D G Hooton, D Green and R A Ainsworth, An R6 Type Approach for the Assessment of Creep Crack Growth Initiation in 316L Stainless Steel Test Specimens, Proc. ASME PVP Conf., Minneapolis, **287**, 129-136, 1994.
5. R A Ainsworth, D G Hooton and D Green, Further Developments of an R6 Type Approach for the Assessment of Creep Crack Incubation, Proc. ASME PVP Conf., Honolulu, **315**, 39-44, 1995.
6. R A Ainsworth, D G Hooton and D Green, Failure Assessment Diagrams for High Temperature Defect Assessment, Engng. Fract. Mech., **62**, 95-109, 1999.
7. R5 Issue 3, An Assessment Procedure for the High Temperature Response of Structures, British Energy Generation Ltd. Procedure, 2003.
8. D G Hooton and D Green, The Determination of Fracture Toughness Values for Use with Time-Dependent Failure Assessment Diagrams, AEA Technology Report SPD/D(96)/579, 1996.
9. D W Dean and D G Hooton, A Review of Creep Toughness Data for Austenitic Type 316 Steels, British Energy Generation, Report E/REP/GEN/0024/00, 2003.
10. J Ewald and K-H Keienburg, A Two-Criteria-Diagram for Creep Crack Initiation, Proc. Int. Conf on Creep, Tokyo, 173-178, 1986.
11. J Ewald and S Sheng, Two Criteria Diagram for Creep Crack Initiation and its Application to an IP-Turbine, Materials at High Temperatures, **15**, 281-288, 1998.
12. J Ewald, S Sheng, A Klenk and G Schellenberg, Engineering Guide to Assessment of Creep Crack Initiation on Components by Two-Criteria-Diagram, Int. J. Pres. Ves. Piping, **78**, 937-949, 2001.

13. D W Dean and R D Patel, A Preliminary Comparison of the R5 Time Dependent Failure Assessment Diagram and the Two Criteria Diagram Approaches for 1CMV Steel, British Energy Generation Ltd. Report, E/REP/BDBB/0029/GEN/03, 2003.
14. D W Dean and R D Patel, A Preliminary Comparison of the R5 Time Dependent Failure Assessment Diagram and 2Criteria Diagram Approaches for Type 316H Steel, British Energy Generation Ltd. Report, E/REP/BDBB/0024/GEN/03, 2003.
15. European Structural Integrity Society, ESIS Procedure for Determining the Fracture Behaviour of Materials, ESIS P2-92, 1992.
16. British Standards Institution, Fracture Mechanics Toughness Tests. Part 4. Method for Determination of Fracture Resistance Curves and Initiation Values for Stable Crack Extension in Metallic Materials, BS 7448: Part 4: 1997, 1997.
17. American Society for Testing and Materials, Standard Test Method for J-Integral Characterization of Fracture Toughness, ASTM E 1737-96, 1996.
18. American Society for Testing and Materials, Standard Test Method for Measurement of Creep Crack Growth Rates in Metals, ASTM E 1457-00, 2000.

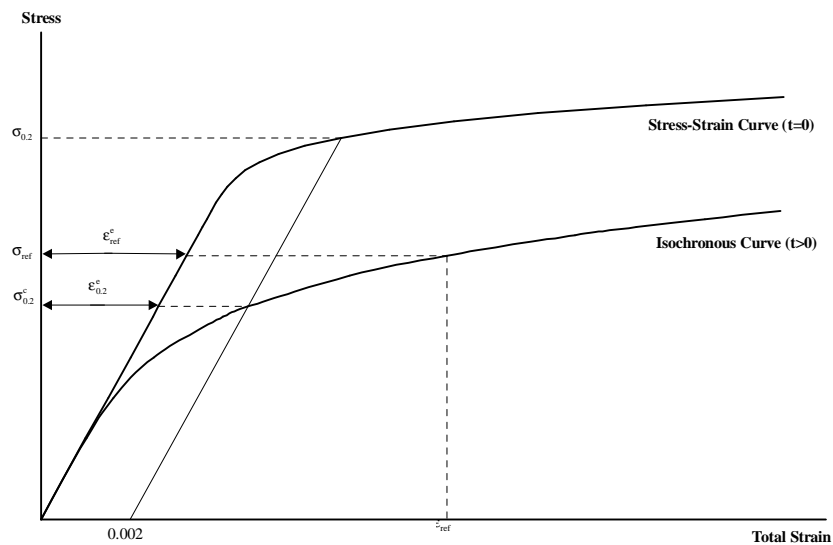


Figure 1 Schematic Isochronous Stress-Strain Curves

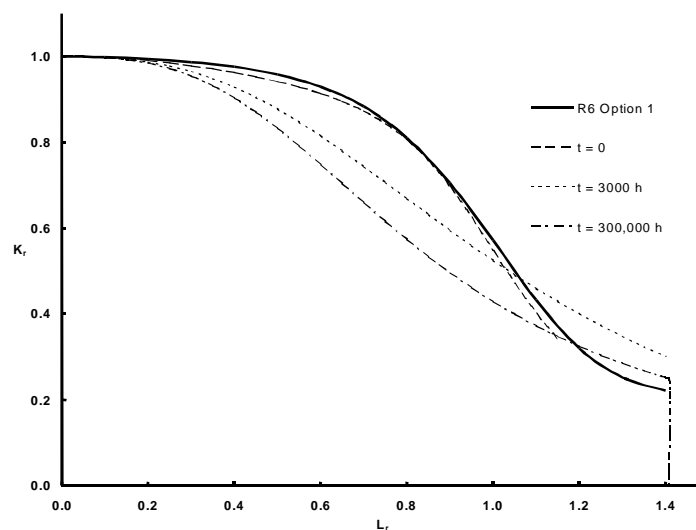


Figure 2 Schematic Failure Assessment Diagrams Based on Data from an Austenitic Type 316 Steel at 600°C

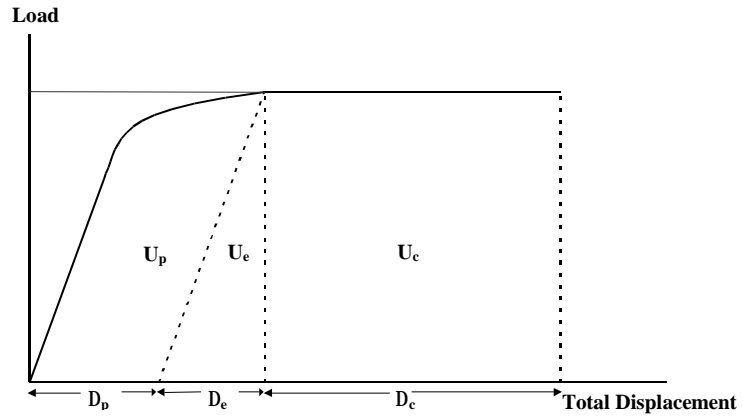


Figure 3 Schematic Load-Displacement Behaviour from a Constant Load Creep Crack Growth Test

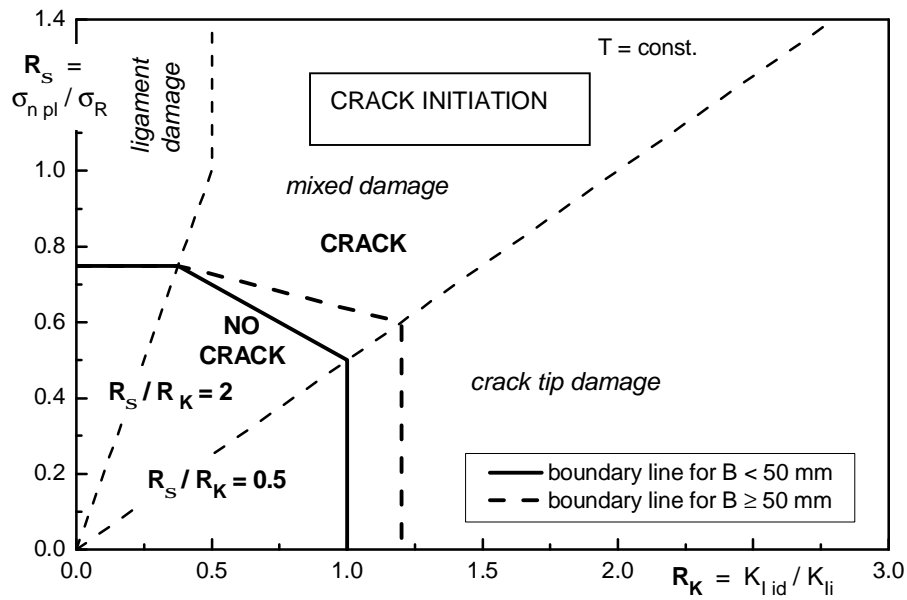


Figure 4 Two Criteria Diagram

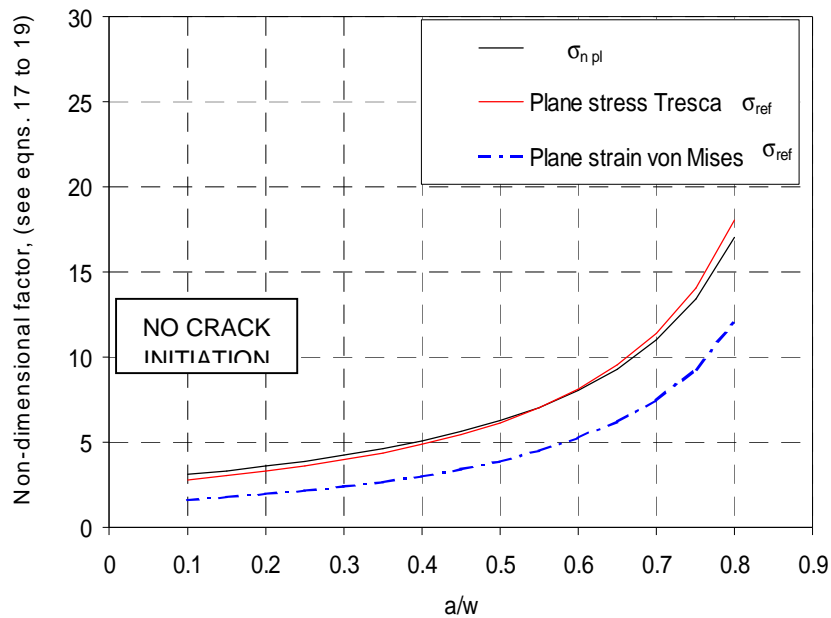


Figure 5(a) Comparison of the Reference Stress, S_{ref} , and Nominal Stress, $S_{n,pl}$

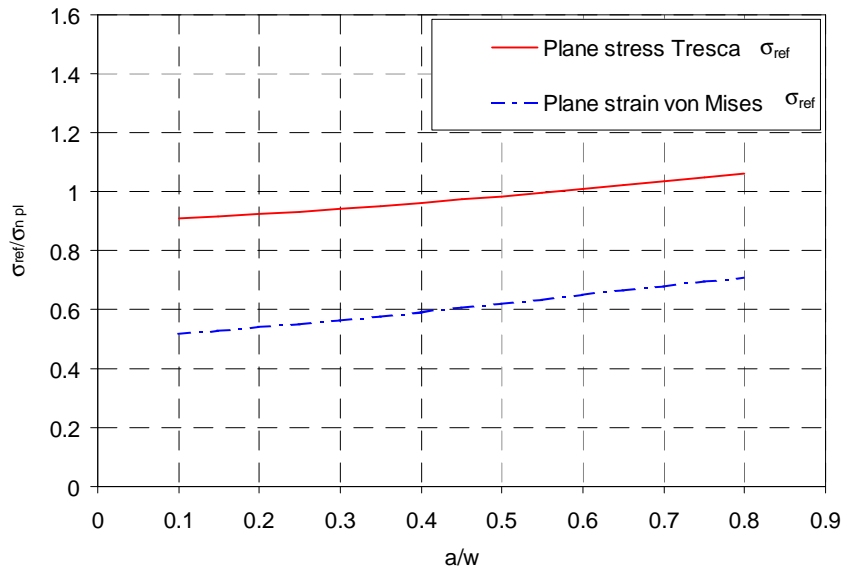


Figure 5(b) Comparison of the Reference/Nominal Stress Ratio

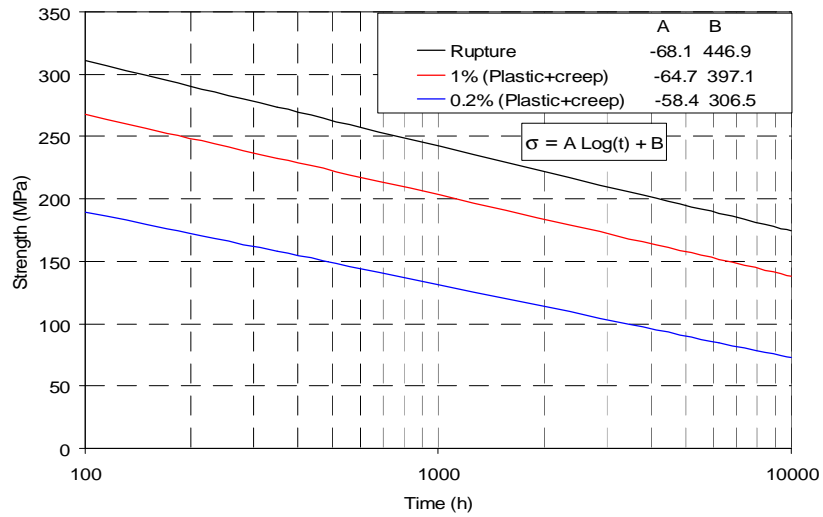


Figure 6(a) Comparison of inelastic strengths with rupture data for 1CMV steel at 550°C

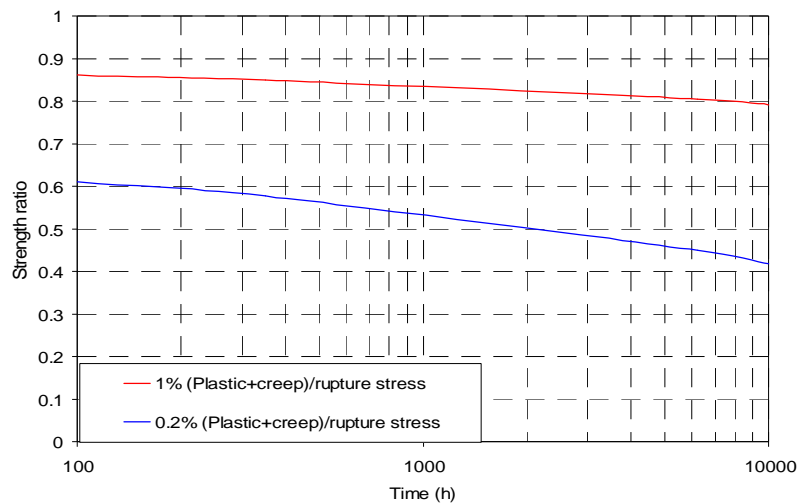


Figure 6(b) Comparison of inelastic strength/rupture strength ratios for 1CMV steel at 550°C

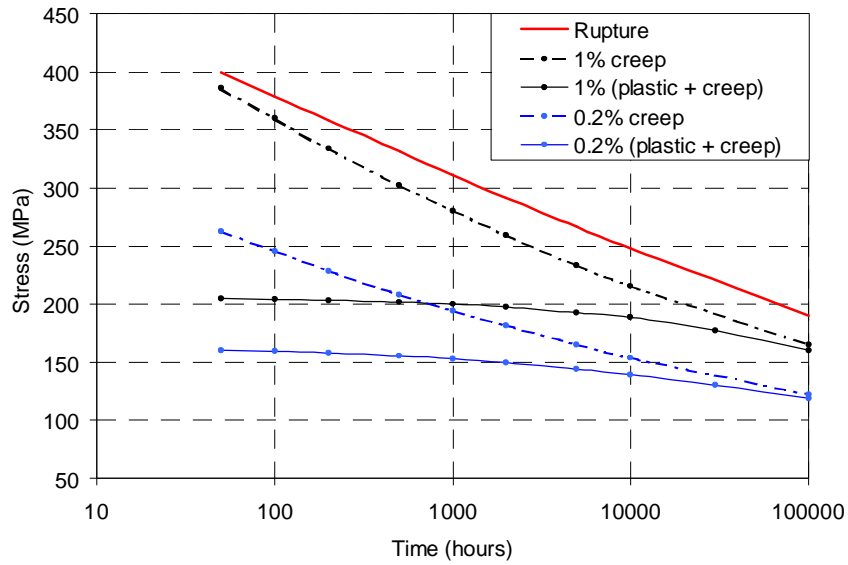


Figure 7(a) Comparison of creep and inelastic strengths with rupture data for Type 316H steel at 550°C

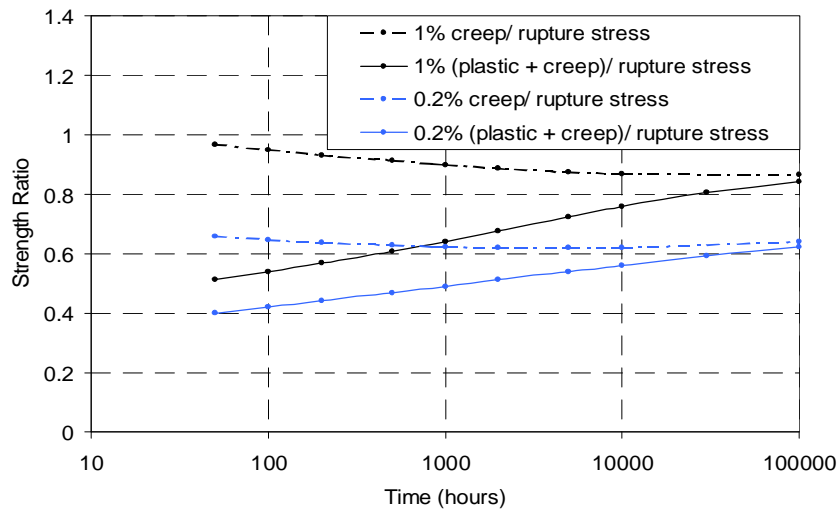


Figure 7(b) Comparison of creep strength/rupture and inelastic strength/rupture ratios for Type 316H steel at 550°C

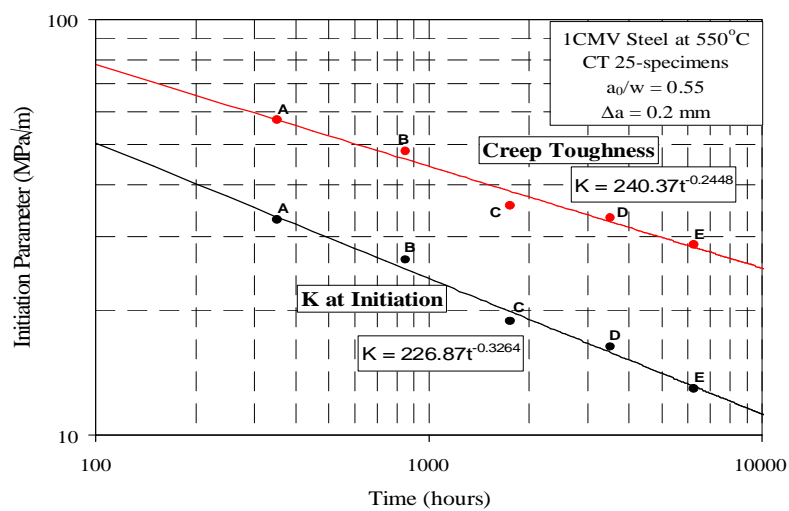


Figure 8 Variation of creep crack initiation parameters with time for 1CMV Steel at 550°C

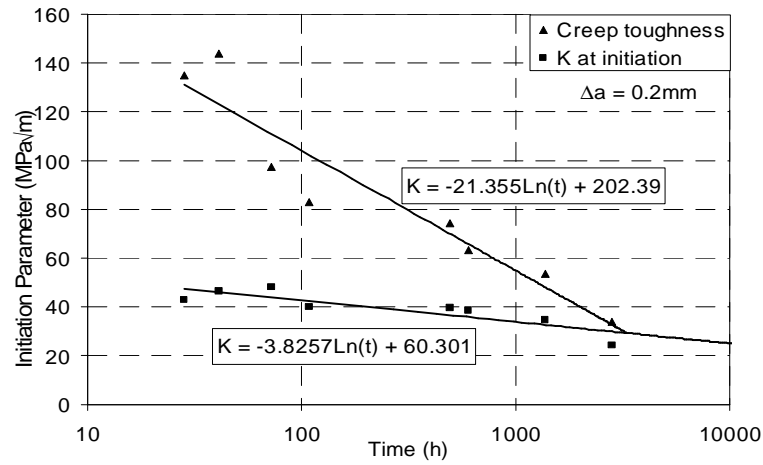


Figure 9 Variation of creep crack initiation parameters with time for Type 316H steel at 550°C

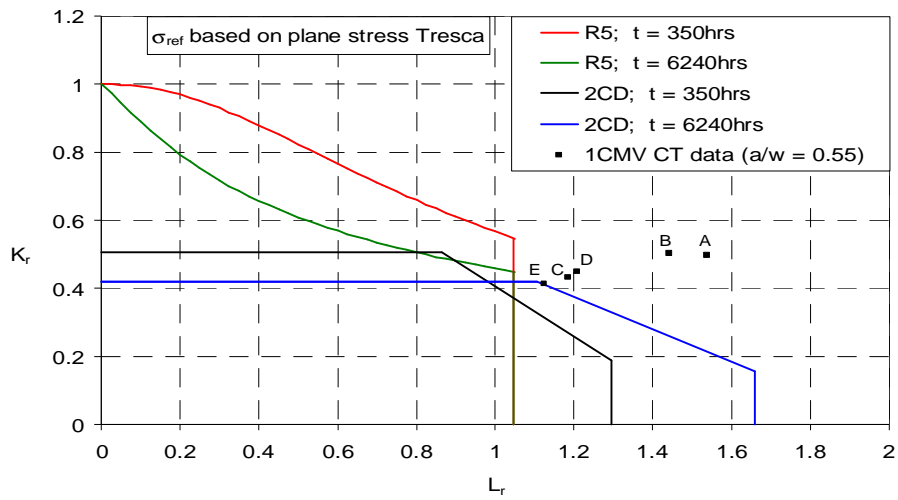


Figure 10(a) R5 TDFAD with superimposed Two Criteria Diagram for 1CrMoV steel at 550°C. S_{ref} is based on Plane Stress Tresca. CT data are also plotted for $Da = 0.2$ mm.

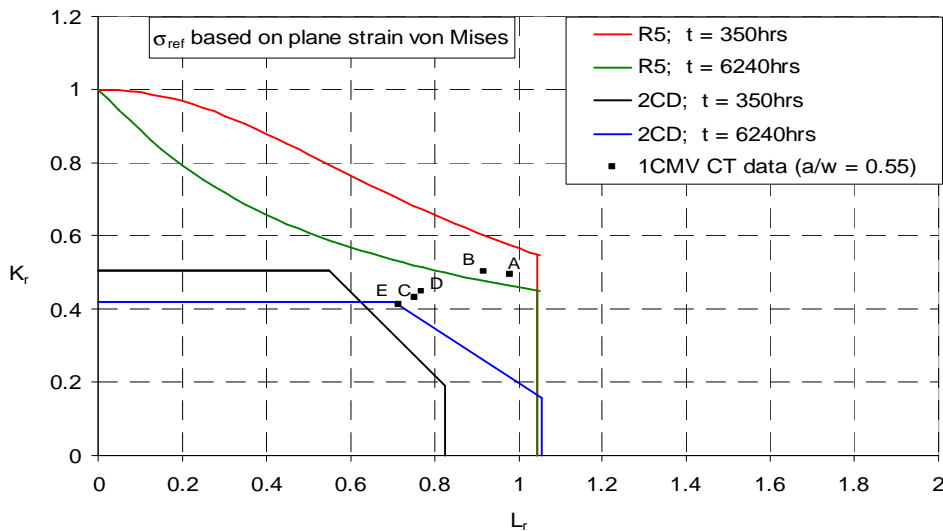


Figure 10(b) R5 TDFAD with superimposed Two Criteria Diagram for 1CrMoV steel at 550°C. S_{ref} is based on Plane Strain von Mises. CT data are also plotted for $Da = 0.2$ mm.

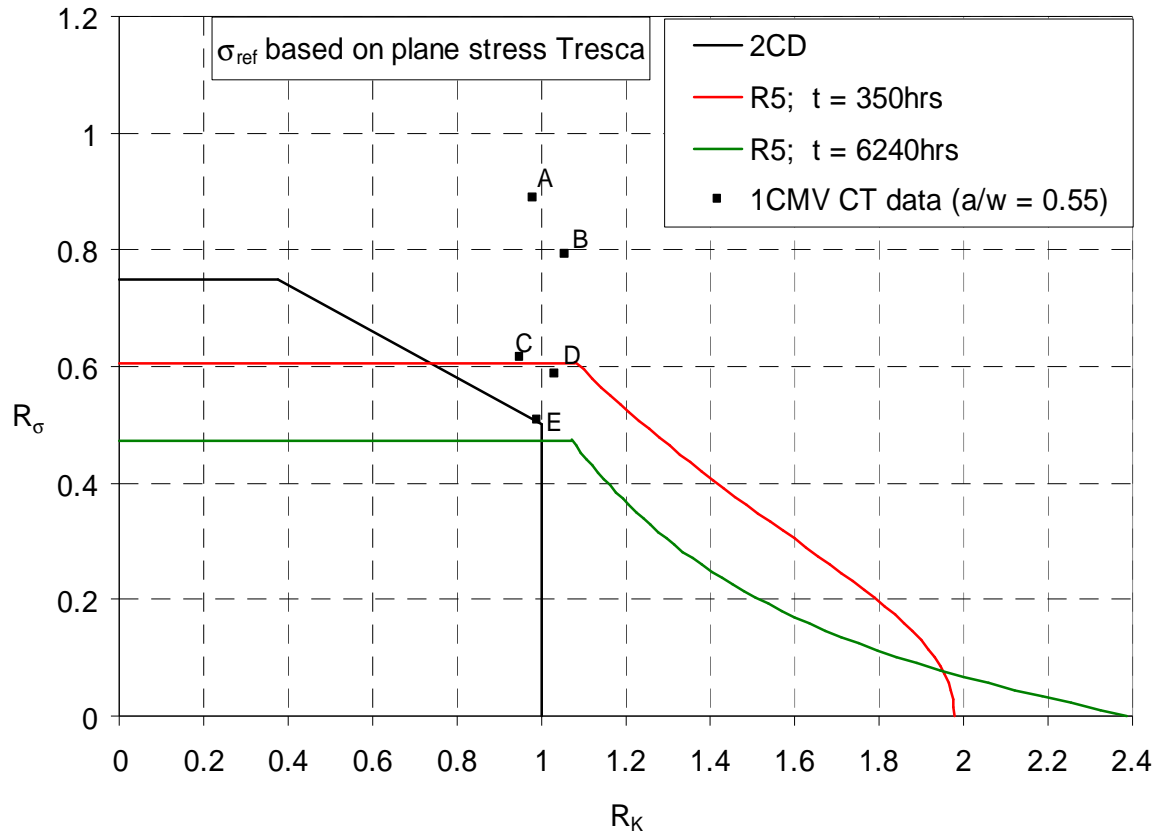


Figure 11(a) Two Criteria Diagram with superimposed R5 TDFAD for 1CrMoV steel at 550°C. S_{ref} is based on Plane Stress Tresca. CT data are also plotted for $Da = 0.2$ mm.

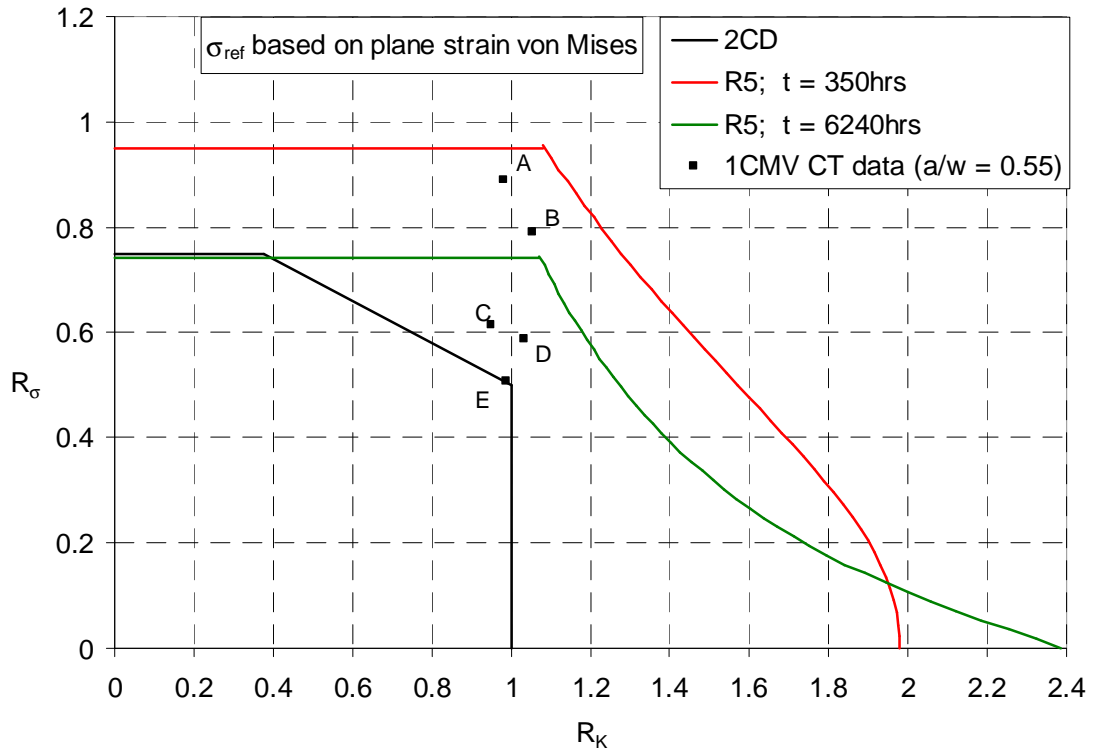


Figure 11(b) Two Criteria Diagram with superimposed R5 TDFAD for 1CrMoV steel at 550°C. S_{ref} is based on Plane Strain von Mises. CT data are also plotted for $Da = 0.2$ mm.

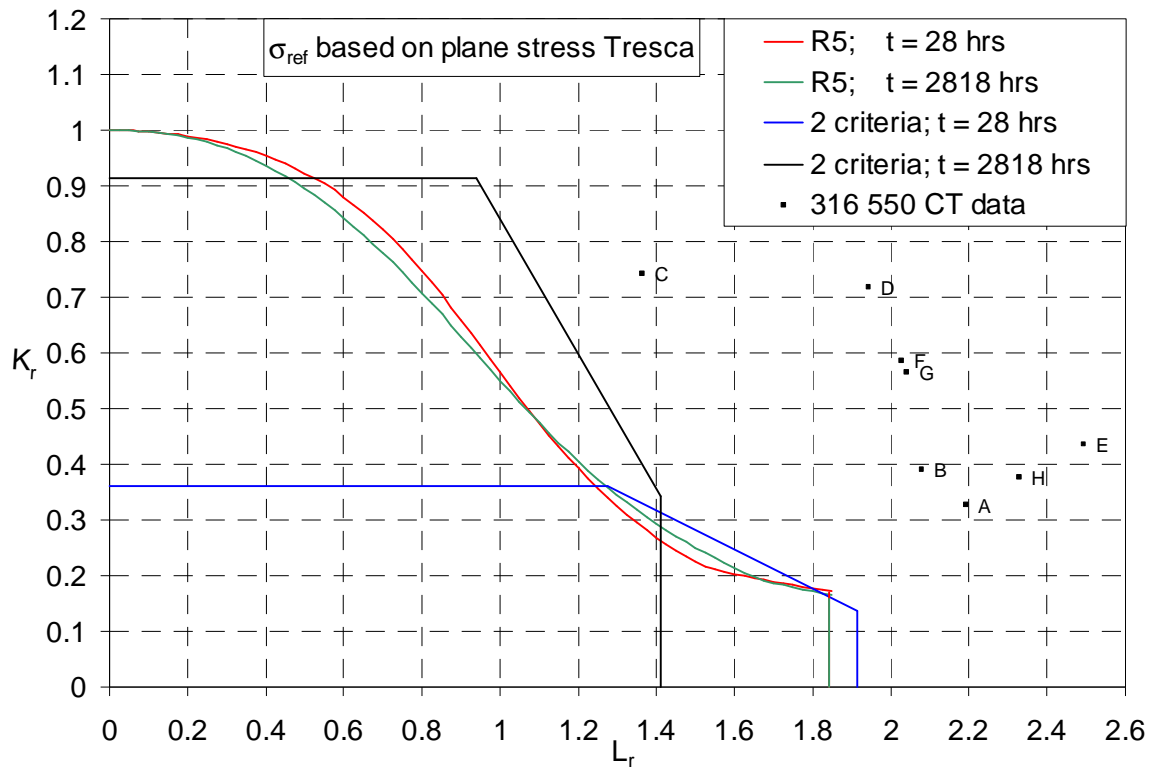


Figure 12(a) R5 TDFAD with superimposed Two Criteria Diagram for Type 316H steel at 550°C. S_{ref} is based on Plane Stress Tresca. CT data are also plotted for $Da = 0.2$ mm.

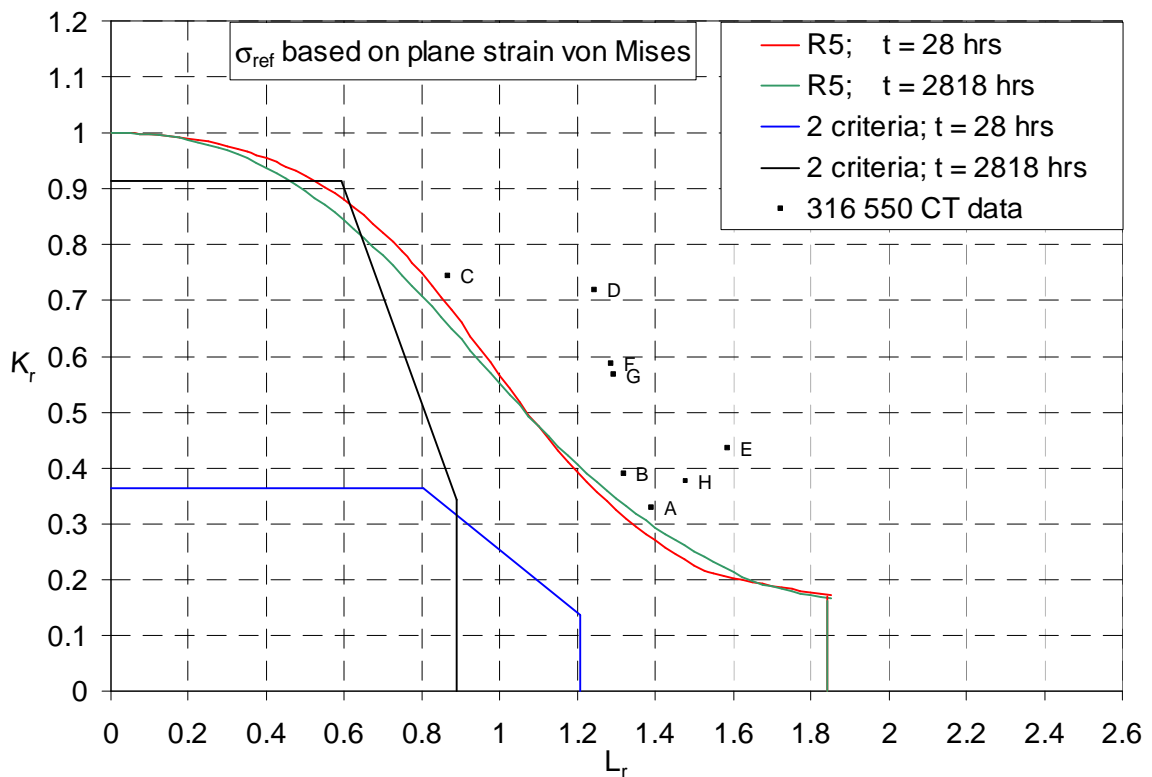


Figure 12(b) R5 TDFAD with superimposed Two Criteria Diagram for Type 316H steel at 550°C. S_{ref} is based on Plane Strain von Mises. CT data are also plotted for $Da = 0.2$ mm.

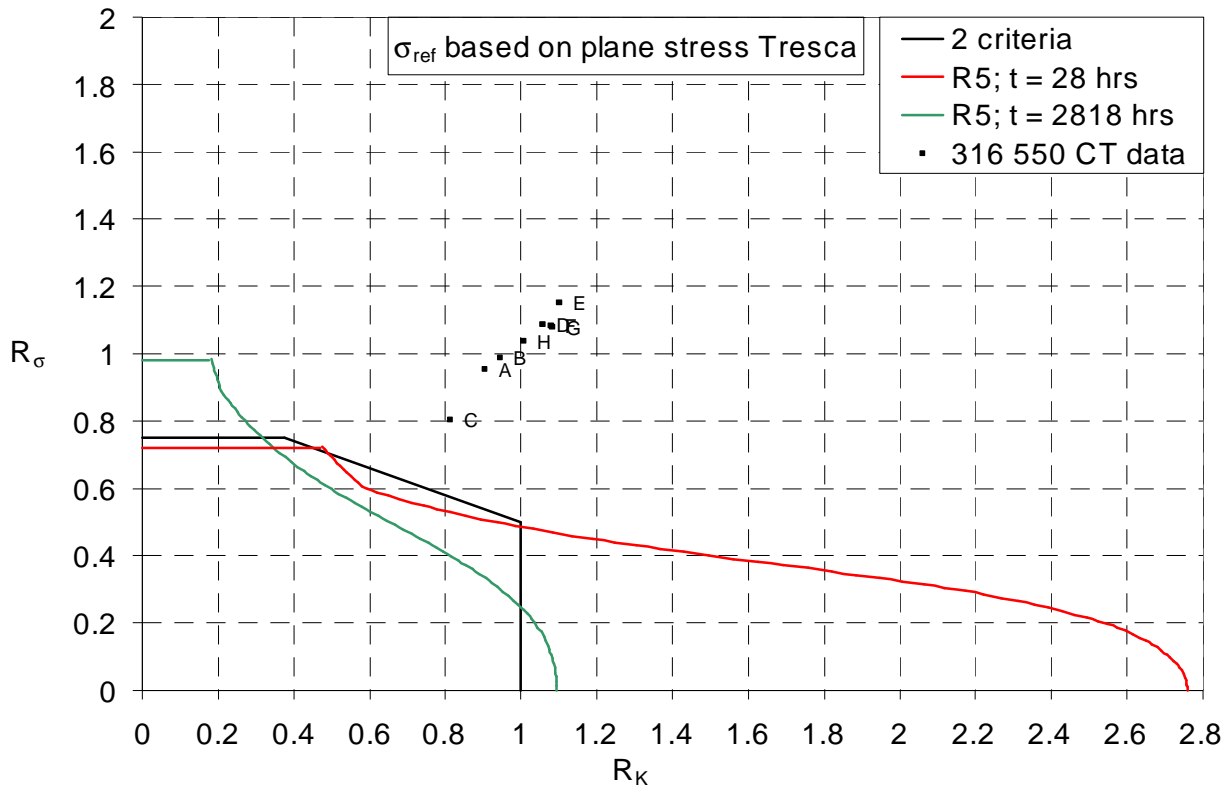


Figure 13(a) Two Criteria Diagram with superimposed R5 TDFAD for Type 316H steel at 550°C. σ_{ref} is based on Plane Stress Tresca. CT data are also plotted for $Da = 0.2$ mm.

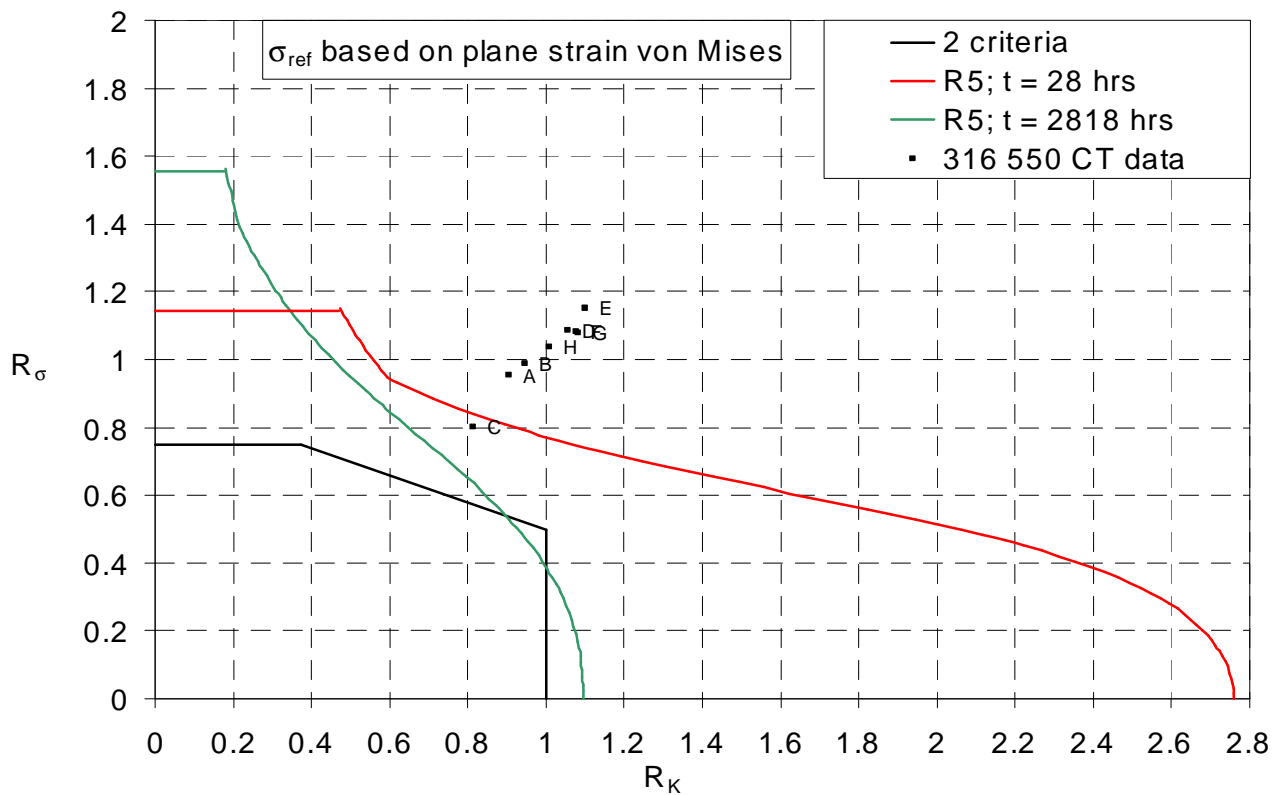


Figure 13(b) Two Criteria Diagram with superimposed R5 TDFAD for Type 316H steel at 550°C. σ_{ref} is based on Plane Strain von Mises. CT data are also plotted for $Da = 0.2$ mm.