K. Wasmer,¹ K. M. Nikbin,² and G. A. Webster²

Prediction of Scatter in Creep Crack Growth Data from Creep Failure Strain Properties

ABSTRACT: Procedures are available for determining the creep crack growth (CCG) properties of materials experimentally in terms of the creep fracture mechanics parameter C^* . When these properties have not been measured, predictions can be made from models of the cracking process. These models show that creep crack growth rate at a given value of C^* is most sensitive to the creep ductility ϵ_f^* appropriate to the state of stress at a crack tip. For plane stress conditions, it is found that ϵ_f^* can be taken to be equal to the uniaxial creep ductility ϵ_f of a material and for plane strain to be given by $\epsilon_f/30$. Hence, in this paper, uniaxial creep properties on type 316 L(N) austenitic stainless steel and two 9 %Cr steels, designated P91 and P92, in the temperature range 500–750°C are reported and scatter in the data identified from statistical analysis. For each steel, the dependence of creep ductility on stress and temperature is determined. It has been found that none of the rupture time (t_R), creep strain rate ($\dot{\epsilon}$), and net section stress (σ_{net}), parameters has a better relationship with the creep failure strain. Hence, none of these parameters characterizes better than the other the creep ductility's behavior. Additionally, it has been observed that although the creep failure strain of 316 L(N) is independent of these parameters, it increases with temperature. In contrast, the creep failure strain of P91 is slightly sensitive to σ_{net} but is overcompensated by the scatter and so can be assumed stress independent. The creep failure strain of P91 is seen to be also insensitive to temperature. For P92, ϵ_f goes from a lower to an upper shelf through a transition region. Thus the best solution to characterize the failure strain behavior is to use a polynomial solution. Creep crack growth properties obtained on cracked compact tension and C-shaped specimens are also presented. Probabilistic analysis, based on Monte Carlo simulation methods, is employed to predict scatter in the creep crack growth data from scatter in the uniaxial creep properties. In most instances, close agreement is found between the experimentally measured scatter in the cracking results and that predicted from the scatter obtained from creep ductility data.

KEYWORDS: uniaxial creep properties, creep ductility, creep crack growth, probabilistic methods

Nomenclature

- A, A_{ave} = constants in creep strain rate laws
- H = constant in creep rupture law
- I_n = nondimensional function of n
- r_c = size of creep damage zone
- $\dot{a}$ = creep crack growth rate
- C^*, C_{Exp}^* = steady-state creep fracture mechanics parameter and experimental C^* value
- D = constant in creep crack growth law
- e_{ϵ_f} = error in creep failure strain
- K = stress intensity factor
- n, n_{ave}, n_s = stress indices in power-law creep equations
- r_{STAT}, r_{STAT}^2 = statistical correlation, coefficient of determination
- SD = standard deviation of the errors

Manuscript received May 7, 2005; accepted for publication September 7, 2005; published December 2005. Presented at ASTM Symposium on Fatigue and Fracture Mechanics: 35th Volume on 18–20 May 2005 in Reno, NV; R. E. Link and K. M. Nikbin, Guest Editors.

¹ Project manager, Swiss Federal Laboratories for Materials Testing and Research (EMPA–Thun), Laboratory for Materials Technology, Feuerwerk-strasse 39, 3602 Thun, Switzerland.

² Principal Research Fellow and Professor, respectively, Department of Mechanical Engineering, Imperial College, London, SW7 2BX, United Kingdom.

- t_R = uniaxial rupture time
 W = width of the specimen
 ϕ = index in creep crack growth law
 $\varepsilon_f, \varepsilon_f^*$ = uniaxial creep failure strain, mean creep failure strain
 ε_f^* = creep ductility appropriate to state of stress
 $\dot{\varepsilon}_{\text{ref}}$ = creep strain rate at the reference stress
 $\dot{\varepsilon}, \dot{\varepsilon}_{\text{ave}}$ = secondary (or minimum) strain rate, average creep strain rate
 $\sigma, \sigma_{\text{ref}}, \sigma_{\text{net}}$ = stress, reference stress, and net section stress
 ν = stress index in creep rupture law

Introduction

In order to predict the lifetimes of components that operate at high temperatures reliably, it is essential to determine their creep rupture and creep crack growth (CCG) behavior accurately. Several design and assessment procedures are available for dealing with this situation. These include the French A16 [2,3], British Energy R5 [4], and BS 7910 [5] codes. Each of these procedures adopts the same basic principles by describing creep strain rate $\dot{\varepsilon}$ and crack growth rate $\dot{a}$ by the power-law relations

$$\dot{\varepsilon} = A \cdot \sigma^n \quad (1)$$

and

$$\dot{a} = D \cdot C^{*\phi} \quad (2)$$

where A , n , D , and ϕ are material constants, σ is stress, and C^* is the creep fracture mechanics parameter [6,7]. In laboratory tests this term is determined experimentally based on the ASTM E 1457 [8] procedure. In components, it is usually estimated from reference stress methods [9,10]. A deterministic approach is employed most often to make assessments and decisions have to be made about whether to choose upper or lower bound material properties to achieve conservative predictions. A worst case combination of bounds may result in excessive conservatism.

Although D and ϕ are best obtained experimentally from tests carried out according to ASTM E 1457 [8], models are available for predicting their values from uniaxial creep data [11,12]. For a creep law of the form of Eq 1 these give

$$\phi = \frac{n}{n+1} \quad (3)$$

and

$$D = \frac{(n+1)}{\varepsilon_f^*} \left[\frac{A \cdot r_c}{I_n^n} \right]^{1/n+1} \quad (4)$$

where r_c is the size of the creep zone at the crack tip in which damage accumulates, I_n is a non-dimensional function of n and state of stress, and ε_f^* is the creep ductility of the material appropriate to the state of stress at the crack tip. For plane stress conditions ε_f^* can be taken as the uniaxial creep ductility ε_f of a material and for plane strain as $\varepsilon_f/30$. Since for most practical purposes $0.7 < \phi < 1$ and the terms in square brackets in Eq 4 are raised to a small fractional power, Eq 2 can often be simplified to

$$\dot{a} = \frac{3 \cdot C^{*0.85}}{\varepsilon_f^*} \quad (5)$$

where $\dot{a}$ is in mm/h, C^* in MPa/m²·h and ε_f^* as a fraction.

Replacing ε_f^* by either ε_f or $\varepsilon_f/30$ in Eq 5, it is evident that D in Eqs 2 and 4, and so CCG predictions, are most sensitive to the creep ductility of a material. Consequently, it may be expected that it should be possible to predict the scatter in creep crack growth data from that recorded in the creep ductility data. To enhance the CCG predictions, it is imperative to have a characterization of the failure strain as close as possible to the reality. In this investigation scatter in uniaxial creep strain rate, rupture and creep ductility data are examined to establish the scatter to be expected in cracking properties. Data on austenitic stainless

steel type 316 L(N) [13,14] and two advanced 9% Cr steels designated P91 [15–23] and P92 [19–24] are considered. The results of the characterization will then be used in a probabilistic method in a latter section.

Materials and Experiments

The data used in this study come mainly from European HIDA, LICON, and CRETE collaborative projects (See Acknowledgment section). Based on these databases, sufficient data were available to allow them to be examined separately as individual batches as well as using them all as one dataset. The nominal chemical compositions of these steels are shown in Table 1. The uniaxial creep data were collected at temperatures in the range 500 to 750°C in accordance with ASTM E 139 [25]. The tests were performed on several casts of the steels. The materials were selected on the basis that they are used in the fabrication of some of high temperature power plant components. Emphasis has been placed on the analysis of creep ductility, secondary, and average creep strain rates defined in Eq 6. Large datasets have been analyzed and the statistical results given in this paper in order to be used as benchmark for CCG predictions.

$$\dot{\epsilon}_{ave} = \frac{\epsilon_f}{t_R} = A_{ave} \cdot \sigma^{n_{ave}} \quad (6)$$

with rupture life t_R expressed as

$$t_R = H \cdot \sigma^{-\nu} \quad (7)$$

where A_{ave} , n_{ave} , H , and ν are material constants and creep crack growth rate. In these equations when $n = \nu$, creep failure strain is independent of stress. When $n_{ave} > \nu$ creep ductility decreases with decrease in stress.

By combining Eqs 6 and 7, ϵ_f can be expressed in the form of

$$\epsilon_f = A_{ave} \cdot H \cdot \sigma^{n_{ave} - \nu} \quad (8)$$

Equation 8 does not predict ϵ_f of each data point but only its means value as well as the sensitivity of the failure strain according to the applied stress. When $n_{ave} = \nu$, ϵ_f is constant and is equivalent to the mean creep failure strain $\bar{\epsilon}_f$, whereas when $n_{ave} > \nu$, ϵ_f increases as σ increases. Therefore, two types of creep failure strain behavior are expected and have been reported by R5 [4]. These are (i) a trend of increasing ductility with increasing net section stress from a lower shelf to an upper shelf and (ii) no clear trend of increasing ductility with stress.

The recommendations of ASTM E 1457 [8] were followed for performing the crack growth tests and in interpreting the results. The results of CCG tests of two types of geometries are presented here which are the compact tension (CT) and c-shape (C). Statistical analysis routines were employed for determining the scatter in the data.

Uniaxial Results

Results of statistical analyses that have been performed on the entire uniaxial creep data are presented in Tables 2–5 for the 316 L(N), P91, and P92 steels, respectively. These tables include information on a wide range of tests on several batches of material. In Table 6 additional results are provided for batches of material on which CCG studies were performed. These tables contain mean values of n , n_{ave} , ν , $\bar{\epsilon}_f$, and standard deviation in ductility $SD \epsilon_f$ at each temperature for all the batches of material combined. Also included in Table 6 are the mean values of D and ϕ obtained from the cracking data in addition to the standard deviation in crack growth rate.

The dependence of creep ductility on secondary creep rate and stress for three batches of 316 L(N) steel at 650°C, from which CCG tests were performed, are shown in Fig. 1. First, it has been found that none of the following parameters, the rupture time (t_R), the creep strain rate ($\dot{\epsilon}$), and the net section stress (σ_{net}), has a better relationship with ϵ_f . Hence, none of these parameters characterizes better than the other the creep ductility's behavior and evidence of this is illustrated in Fig. 1 and Table 2 with the statistical correlation value r_{STAT} . Second, it is difficult to establish a clear trend between different casts. This behavior was expected since it has been observed from Table 2, that $n_{ave} \approx n_s \approx \nu$ for 316 L(N)–PM. Since

ε_f is not stress dependent and that no cast influence is perceived (see Fig. 1), it is possible to analyze all creep failure ductility results regardless their cast and origin. This is supported further in Fig. 2 where the creep failure strain is plotted on a normal probability diagram for all the 316 L(N) tests at 650°C. The visual examination of this figure demonstrates that, except for a few points, the data are normally distributed and this is corroborated by a $r_{STAT}=0.98$. This proves that creep failure strain data can be assumed to be insensitive to the stress and normally distributed. The dependence of creep ductility on stress for the entire dataset is presented in Fig. 3 together with the upper and lower two standard deviation (2SD) bounds. It is apparent, within the range of scatter observed, that creep failure strain can be regarded as independent of stress for this temperature. Similar trends were observed for the other temperatures examined. The mean, standard deviations, and correlation coefficients obtained for each temperature are listed in Table 2. This table and Fig. 4 indicate that the mean creep ductility and the standard deviations for each temperature for 316 L(N) stainless steel increase with temperature. The ± 2 standard deviation ($\pm 2SD$) bounds for the average creep strain rate at 650°C are shown in Fig. 5 as a function of net section stress. These approximate to a range of about times 22.

The creep failure strain behavior of the two 9 %Cr steels are different as those obtained on the 316 L(N) stainless steel as indicated in Tables 3 and 4. Illustrations of the scatter obtained in creep ductilities are shown in Figs 6–9 for the P91 steel. Based on Fig. 6, the P91 creep ductility seems to increase with the net section stress. This is consistent with Eq 8 in conjunction with the results given in Table 3 where $n_{Ave} > \nu$. However, this trend disappears when all individual batches of material are combined into one

FIG. 1—The effect of (a) secondary creep rate and (b) stress on the creep failure strain for three casts of 316 L(N) steel at 650°C.

FIG. 2—Normal probability plot of creep failure strain for all tests on 316 L(N) steel at 650°C.

FIG. 3—Creep failure strain as a function of stress for all tests on 316 L(N) steel at at 650°C.

FIG. 4—Effect of temperature on the creep failure strain for all tests on 316 L(N) steel.

FIG. 5—Average creep strain rate for all tests on 316 L(N) steel at 650°C.

dataset as evidence from Figs. 7–9. Based on these figures, it is evident that, for the P91 steel, ϵ_f can be regarded as independent of stress, and so normally distributed. This is demonstrated by making this assumption and testing with the normal probability plot as in Fig. 7. Figure 8 illustrated the results of the complete dataset available for P91 including the mean and ± 2 standard deviations. Furthermore, P91 is, in contrast to 316 L(N), insensitive to temperature, and evidence of this is in Fig. 9. Also dissimilar to 316 L(N) stainless steel, its scatter for the total dataset rises with an increase in temperature only between 500 and 550°C. This may be due to the small number of tests available at 500°C.

The scatter in ϵ_f for P92 is presented in Figs 10–12. These figures show that ϵ_f increases with both stress and temperature. The stress dependence can be interpreted in terms of a lower and upper shelf ductility, with a transition region, as reported in R5 - British Energy [4] and seen in Fig. 10, or by a polynomial expression as indicated in Figs 11 and 12. The fitting coefficients to a fifth degree polynomial fit are listed in Table 5. The purpose of the table is to be used as benchmark when no P92 uniaxial data are available for CCG predictions. Even if r^2_{STAT} , the coefficient of determination, in Table 5 are not high, the polynomial expression is by far the simplest method to represent the creep ductility behavior since determining the lower and upper shelves linked by the transition only on a statistical basis is not viable. In all cases, it has been found that results on individual batches of material can be combined into one dataset for statistical analysis.

FIG. 6—The effect of net section stress on the creep failure strain for of P91 steel at 600°C.

FIG. 7—Normal probability plot of creep failure strain for all tests on P91 steel at 600°C.

FIG. 8— ϵ_f dependence on σ_{net} for all P91 casts at 600°C assuming normal distribution.

FIG. 9—Effect of temperature on creep failure strain for all casts of P91 steel.

FIG. 10—Effect of ϵ_f on σ_{net} for (a) specific casts and (b) all casts of P92 steel at 600°C.

FIG. 11—Fit of polynomial of degree five to all creep ductility data on P92 steel at 600°C.

FIG. 12—Effect of temperature on creep failure strain for all tests on P92 steel.

Creep Crack Growth Results

The results of statistical analysis that have been carried out on the experimental creep crack growth data are given in Table 6 and in Fig. 13. These results will be used in the prediction of creep crack growth section. Also included in Table 6 are the uniaxial material properties obtained on individual batches of the steels used to make the probabilistic calculations based on Monte Carlo simulations (MCS). Figure 13(a) shows that the scatter in CCG rate results for the 316 L(N) stainless steel is similar to that of the multicast uniaxial creep data of Fig. 5 although only two batches of the material were tested for the cracking experiments. However, in addition, two sizes of CT specimens were examined. In contrast, in Fig. 13(b) for the more creep brittle 9 %Cr steel, only one cast of material and one size of the c-shaped specimen were examined and the scatter is found to be much lower.

TABLE 1—Chemical compositions of 316 L(N), P91 and P92 (in weight percent).

Mat.	C	Si	Mn	P	S	Cr	Cu	Mo	N	Nb	Ni	V	W
316 L(N)	0.040	0.310	1.830	0.036	0.020	17.30	0.030	2.460	0.070	-	11.90	-	-
P91	0.106	0.320	0.470	0.016	0.001	8.930	0.110	0.940	0.065	0.067	0.300	0.210	-
P92	0.114	0.190	0.410	0.020	0.008	9.370	0.090	0.470	-	0.055	0.230	0.190	1.720

TABLE 2—Statistical results of creep analysis for multicasts 316 L(N)-PM steel.

Material	Temp. (°C)	No. of tests	n_{Ave}	n_s	ν	$\bar{\epsilon}_f$	$SD \epsilon_f$	r_{STAT} for ϵ_f
316 L(N)	500	11	11.63	16.59	8.78	0.30	0.07	0.97
316 L(N)	550	127	11.74	10.15	10.79	0.30	0.09	0.95
316 L(N)	600	124	8.96	8.76	9.38	0.41	0.15	1.00
316 L(N)	650	82	7.37	8.27	7.42	0.54	0.15	0.98
316 L(N)	700	24	5.98	6.63	6.26	0.72	0.21	0.99
316 L(N)	750	15	5.78	5.78	5.47	0.80	0.16	0.90

TABLE 3—Statistical results of creep analysis for multicasts P91-PM steel.

Material	Temp. (°C)	No. of tests	n_{Ave}	n_s	ν	$\bar{\epsilon}_f$	$SD \epsilon_f$	r_{STAT} for ϵ_f
P91	500	11	20.81	N / A	21.22	0.27	0.03	0.95
P91	550	110	13.87	N / A	12.89	0.24	0.07	0.99
P91	600	238	9.41	13.51	8.73	0.27	0.08	0.99
P91	650	145	7.98	N / A	7.37	0.30	0.09	0.99
P91	700	13	6.71	N / A	6.48	0.32	0.09	0.98
P91	500–700	668	N / A	N / A	N / A	0.27	0.09	0.99

TABLE 4—Statistical results of creep analysis for multicasts P92-PM steel.

Material	Temp. (°C)	No. of tests	n_{Ave}	n_s	ν	$SD \epsilon_f$
P92	550	49	18.97	18.62	18.63	0.03
P92	600	125	16.15	14.88	14.76	0.06
P92	650	130	11.81	11.56	10.40	0.05
P92	700	70	8.13	8.53	7.46	0.06
P92	750	8	6.74	7.35	6.23	0.08

TABLE 5—Statistical results of multicasts creep failure strain for P92a.

Material	Temp. (°C)	No. of tests	$\sigma_{net Max}$ (MPa)	$\sigma_{net Min}$ (MPa)	σ_{net}^5	σ_{net}^4	σ_{net}^3	σ_{net}^2	σ_{net}^1	σ_{net}^0	r_{STAT}^2 for polynomial expression
P92	550	56	210	350	$5.57 \cdot 10^{-13}$	$-9.98 \cdot 10^{-11}$	$6.44 \cdot 10^{-7}$	$-3.69 \cdot 10^{-4}$	$8.14 \cdot 10^{-2}$	-6.15	0.65
P92	600	125	135	280	$-2.92 \cdot 10^{-11}$	$3.30 \cdot 10^{-8}$	$-1.45 \cdot 10^{-3}$	$3.10 \cdot 10^{-3}$	$-3.15 \cdot 10^{-1}$	12.30	0.76
P92	650	130	70	250	$5.78 \cdot 10^{-12}$	$-4.51 \cdot 10^{-9}$	$1.37 \cdot 10^{-6}$	$-2.18 \cdot 10^{-4}$	$2.12 \cdot 10^{-2}$	-0.74	0.90
P92	700	70	40	160	$-1.81 \cdot 10^{-11}$	$4.68 \cdot 10^{-9}$	$3.92 \cdot 10^{-8}$	$-2.35 \cdot 10^{-4}$	$2.62 \cdot 10^{-2}$	0.60	0.77
P92	750	8	30	70	$-1.28 \cdot 10^{-9}$	$3.34 \cdot 10^{-7}$	$-309 \cdot 10^{-5}$	$-1.13 \cdot 10^{-3}$	$6.57 \cdot 10^{-3}$	0.07	0.65

TABLE 6—Experimental creep crack growth results and uniaxial data used in MCS.

Experimental creep crack growth results										Experimental uniaxial creep results							
Material ^a	Batch	Temp. (°C)	Spec.	No. of tests/points	Log(D)	ϕ	$\dot{a}$	$\pm 2SD$	r_{STAT}^2	No. of tests	Ratio _D	A_{ave}	n_{Ave}	$\bar{\epsilon}_f$	$SD \epsilon_f$	Ratio $\pm 2SD$	r_{STAT} for ϵ_f
316 L(N)	HIDA	650	CT	7/89	0.44	0.83	0.30	16.0	0.95	5	2.74	1.9E-22	8.35	0.54	0.15	3.5	0.99
P91	LICON	600	C-shape	6/109	0.69	0.70	0.16	4.4	0.93	8	1.33	1.2E-32	13.30	0.27	0.09	5.0	0.99
P92	LICON	625	C-shape	2/47	0.92	0.75	0.11	2.8	0.98	6	1.49	7.4E-34	13.59	0.18	0.05	3.5	0.99

^aDataset for 316 L(N)-PM-CT specimens comes from the HIDA project. In contrast, the dataset for P91 and P92-C-shaped specimens comes from the LICON project.

FIG. 13—Experimental creep crack growth results for (a) 316 L(N)-PM-CT at 650°C and (b) P91-PM-C25 at 600°C.

Prediction of Creep Crack Growth Data

Monte Carlo simulation (MCS) methods [1,26,27] have been applied to predict the scatter in the crack growth data from the uniaxial creep properties. Two procedures were employed. In one instance, values of C^* within the experimental range were chosen at random and estimates of crack growth rate obtained from

$$\dot{a} = \frac{D}{\left(1 + \frac{e_{\varepsilon_f}}{\varepsilon_f}\right)} C^{*\phi} \quad (9)$$

where the values of D and ϕ were taken from Table 6 to correspond with the specific batches of the steels used in the CCG tests. Equation 9 allows the scatter in the creep failure strain data to be compared with the one observed in the creep crack growth tests. In fact, in this equation, ε_f is the mean creep failure strain and e_{ε_f} is the error in this strain that is chosen randomly in the Monte Carlo simulation. The values of e_{ε_f} correspond with the distribution in experimental failure strains obtained from the statistical analysis performed on the single batch uniaxial data shown in Table 6. The predictions for each material are shown in Figs. 14(a) and 15. Almost identical bounds for the 9 %Cr steels are obtained to those measured experimentally. In contrast to 316 L(N), the predicted bounds is more or less four times less than the experimental one. The increased CCG experimental scatter for 316 L(N) stainless steel is attributed to three main factors. First, the highly ductile cracking behavior in this steel (see Fig. 4) at 650°C produces a larger scatter of a factor of 16 between $\pm 2SD$ [see Fig. 13(a)] compared to P91 [Fig. 13(b)] which gives a scatter *factor of 5. The first reason is the exceptionally large scatter observed between $\pm 2SD$ [factor 16 in Figs. 13(a) and 15(a)] for the creep crack growth data [1]. Second, in the present dataset for the 316 L(N) stainless steel, two material batches and two CT specimen sizes were used (CT with the width $W=25$ and 50). This may necessitate the use of two values of ε_f^* to allow for the effect of different constraints in the two sizes of specimens. Finally, for a material with creep ductility $<50\%$, the ratio between $\pm 2SD$ will always be less than four assuming a standard deviation of 0.15. This comes from the fact that the ratio is calculated from

$$\text{Ratio } \pm 2SD = \frac{\overline{\varepsilon_f} + 2SD}{\overline{\varepsilon_f} - 2SD} \quad (10)$$

It is obvious that assuming a constant standard deviation, the ratio between $\pm 2SD$ is only dependent on $\overline{\varepsilon_f}$. Higher is this value, smaller is the ratio $\pm 2SD$. It can be concluded from these two statements that the creep failure ductility must not be used to predict the scatter in creep crack growth data when $\overline{\varepsilon_f} > 0.5$ and $SD \dot{a} > 10$. Finally, it is apparent, in all cases, that the cracking data can be correlated by an expression of the form of Eq 2. The average values obtained for D and ϕ , together with the standard deviations produced in crack propagation rate, are listed in Table 6. Bounds for the two standard deviations spread in the

FIG. 14—Comparison between experimental and predicted scatter in crack growth data for P91 steel at 600°C when (a) C^* is determined experimentally and (b) C^* is calculated from reference stress methods.

FIG. 15—Comparison between experimental and predicted scatter in creep crack growth data and C^* determined experimentally for (a) 316 L(N) steel at 650°C and (b) P92 steel at 625°C.

experimental data are included in the figures. It is apparent, in all cases, that the cracking data can be correlated by an expression of the form of Eq 2.

Comparisons were also made using the alternative procedure for predicting scatter in crack growth data. In this instance, C^* was determined by reference stress methods [9,10] from

$$C^* = \sigma_{ref} \cdot \dot{\epsilon}_{ref} \cdot \left(\frac{K}{\sigma_{ref}} \right)^2 \quad (11)$$

where K is stress intensity factor and $\dot{\epsilon}_{ref}$ is the creep strain rate at reference stress σ_{ref} . It has already been shown that creep crack growth predictions are sensitive to the reference stress formula and creep strain rates [1] and [28,29]. Consequently, the Monte Carlo simulation procedure was employed as previously except in this case C^* was calculated from Eq 11. To avoid the influence of the reference stress and materials properties, these parameters were selected to give the best approximation of the experimental C^* , C^*_{Exp} . For the test C1-PM, the best σ_{ref} is taken from plane strain—Von Mises (Pε—VM). The mean average creep rate, obtained from rupture data, was used in the calculations to determine $\dot{\epsilon}_{ref}$, without taking into account its scatter to only investigate the influence of variation in ϵ_f , to allow approximately for all stages of creep. The material properties employed are based on the average strain rate and are given in Table 6.

The results are presented in Fig. 14(b). Again a virtually identical spread in the data is predicted to that measured experimentally. It is evident, whichever method of determining C^* is adopted, that similar overall predictions of experimental scatter can be replicated by the MCS method. The analysis demonstrates that experimental scatter in creep crack growth data can be predicted from the scatter in uniaxial creep rupture strain when $\bar{\varepsilon}_f > 0.5$ and $SD \dot{a} > 10$.

Conclusions

The scatter in uniaxial creep data on type 316 L(N) stainless steel and two 9 %Cr steels designated P91 and P92 has been analyzed statistically. It has been found that none of the rupture time (t_R), the creep strain rate ($\dot{\varepsilon}$), and the net section stress (σ_{net}), has a better relationship with the ε_f . Hence, none of these parameters characterizes better than the other the creep ductility's behavior. Additionally, the results from different batches of one material can be treated individually but that a clear trend can be established only when they are treated as one large dataset with the variability in creep ductility exhibiting a normal distribution with a bigger standard deviation to that of an individual batch of material. It has also been established that the creep failure strains of the 316 L(N) stainless steel and the P91 steel are independent of stress whereas, for the P92 steel, creep failure strain increases with stress. In addition it has been shown for all the steels that the standard deviation in creep ductility tends to increase with an increase in temperature. However, this does not necessarily imply an increase in scatter since the ratio between $\pm 2SD$ is strongly dependent on $\bar{\varepsilon}_f$. A probabilistic approach has been adopted, using Monte Carlo simulation methods, to predict the expected scatter in creep crack growth data from that experienced by the creep failure strain. It is demonstrated for each material that close agreement is achieved, in most instances, with the experimental scatter observed in crack growth tests for conditions where $\bar{\varepsilon}_f > 0.5$ and $SD \dot{a} > 10$. The results of this investigation indicate, that when only sparse creep crack growth information is available, the scatter in the data can be predicted from the scatter in creep ductility irrespective of whether C^* is determined experimentally or by reference stress methods. Due to the increase in scatter observed in creep failure strain with an increase in temperature, it is anticipated that, for materials where $\bar{\varepsilon}_f$ is insensitive to the temperature, as for P91, the spread in creep crack growth data should also get larger as the test temperature rises.

Acknowledgments

The authors would like to acknowledge the provision of data from the European Brite/Euram "HIDA" (1996–2000), "LICON" (1997–2001), and CRETE (2001–2004) project partners.

References

- [1] Wasmer, K., "Prediction of Creep Crack Growth for a Range of Steels," Ph.D. Thesis, Mechanical Engineering Department, Imperial College, London, 2003.
- [2] Commissariat à l'Energie Atomique. A16, "Guide for Defect Assessment and Leak Before Break Analysis," 3rd ed., Saclay, CEA, 1995.
- [3] Commissariat à l'Energie Atomique. A16, "Guide for Defect Assessment and Leak Before Break Analysis," 4th ed., Saclay, CEA, 2002.
- [4] R5-British Energy, "Defect Assessment Code of Practice for High Temperature Metallic Components," British Energy Generation Ltd., 1999.
- [5] BS 7910, "Guide on Methods for Assessing the Acceptability of Flaws in Fusion Welded Structures," London, BSI, 2000.
- [6] Nikbin, K. M., Webster, G. A., and Turner, C. E., *Relevance of Non-Linear Fracture Mechanics to Creep Cracking, Cracks and Fracture*, ASTM STP 601, Pittsburgh, pp. 47–62, 1976.
- [7] Webster G. A. and Ainsworth R. A., *High Temperature Components Life Assessment*. Chapman & Hall, London, 1993.
- [8] ASTM Standard E 1457-00, "Standard Test Method for Measurement of Creep Crack Growth Rates in Metals," Annual Book of ASTM Standards, Vol. 3, No. 1, ASTM International, West Conshohocken, PA, 2000.

- hocken, 936–950, (2001).
- [9] Ainsworth, R. A., “Some Observations on Creep Crack Growth,” *Int. J. Fract.*, 20, 147–159 (1982).
 - [10] Ainsworth, R. A., “The Assessment of Defects in Structure of Strain Hardening Materials,” *Eng. Fract. Mech.*, 19, 633–642 (1984).
 - [11] Nikbin, K. M., Smith, D. J., and Webster, G. A. “Influence of Creep Ductility and State of Stress on Creep Crack Growth,” *Advances in Life Prediction Methods at Elevated Temperatures*, ASME International Conference, New York edited by D. A. Woodford and J. R. Whitehead 1983, 249–258 (1983).
 - [12] Nikbin, K. M., Smith, D. J., and Webster, G. A. “Prediction of Creep Crack Growth from Uniaxial Creep Data,” *Proc. R. Soc. London, Ser. A* 396, 183–197 (1984).
 - [13] Lehmann, D., “Final Report: Evaluation of the Stress to Rupture and Creep Properties of Type 316 L(N) Steel for Design Use,” European Commission: Nuclear Science and Technology, EUR-16168, 1995.
 - [14] Hyde, T. H., “Creep of 316 Stainless Steel at 500° and 600°C and the Effects of Short Duration Overloads on Creep at 550°C,” *Mater. High. Temp.*, 14,(1), 27–35 (1997).
 - [15] NIRM Creep Data Sheet No. 43, “Data Sheets on the Elevated Temperature Properties of 9Cr-1Mo-V-Nb Steel Plates for Boilers and Pressure Vessels (ASME SA-387/SA-387M Grade 91), 1996.
 - [16] Bendick, W., “*Damage Assessment on P91 Specimens from Uniaxial Creep Tests: Final Report*,” Mannesmann Forschungsinstitut, LICON/MFI 016/TR07, 1999.
 - [17] Prunier, V., Gampe, U., Nikbin, K. M., and Shibli, A., “HIDA Activity on P91 Steel,” *Mater. High. Temp.*, 15, 35–42 (1998).
 - [18] Schuster, F. A. and Hanus, R., “Foundry Experience in Large Turbine Casings and Valve Bodies made of Steel Castings P91 and G-X12 CrMoWVNbN 10 11,” Paper presented at the *Creep and Fatigue*, London, 1999, 11–22.
 - [19] Hald, J., “Creep Strength and Ductility of 9 to 12% Chromium Steels,” *Mater. High. Temp.* 21(1), 41–46 (2004).
 - [20] Ricci, N. and Bontempi, P., “Metallographic Examination of P91, P92 and E911 Specimens Tested in the Frame of the LICON Task 3,” *Centro Elettrotecnico Sperimentale Italiano*, LICON/CESI011/PR08, 2000.
 - [21] Taylor, N., Lucon, E., Bicego, V., and Bontempi, P., “Crack Stability Assessment of Advanced 9CR Steels in Boilers Components,” Paper presented at the *Advanced Steam Plant*, London, 1997, pp. 201–210.
 - [22] Verelst, L., “Creep Test Results of Accelerated Damage Enhancement (ADE) Testing,” LABORELEC, LICON/LE 007/TR03, 1998.
 - [23] Holdsworth, S. R. and Davies, R. B., “A Recent Advance in the Assessment of Creep Rupture Data,” *Nucl. Eng. Des.*, 190,(3), 287–296 (1999).
 - [24] NIRM Creep Data Sheet No. 48 Data Sheets on the Elevated-Temperature Properties of 9Cr-0.5Mo-1.8W-V-Nb Steel Pipe for High Temperature Service (ASME SA-335/SA-335M Grade P92), 2002.
 - [25] ASTM Standard E 139-00, “Standard Test Method for Conducting Creep, Creep-Rupture and Stress-Rupture Tests of Metallic Materials,” *Annual Book of ASTM Standards*, Vol. 3(1), West Conshohacken, PA, pp. 270–281, 2001.
 - [26] Nikbin, K. M., Yatomi, M., Wasmer, K., and Webster, G. A., “Probabilistic Analysis of Creep Crack Initiation and Growth in Pipes Components,” *Int. J. Pressure Vessels Piping*, 80(7-8), 585–595 (2003).
 - [27] Wasmer, K., Nikbin, K. M., and Webster, G. A., “Sensitivity of Creep Crack Initiation and Growth in Plates to Material Properties Variations,” *J. Am. Inst. Electr. Eng.*, 2(1) (2005).
 - [28] Wasmer, K., Nikbin, K. M., and Webster, G. A. “A Sensitivity Study of Creep Crack Growth in Pipes,” PVP Vol. 438, *New and Emerging Computational Methods: Applications to Fracture, Damage and Reliability*, ASME, New York, 2002, pp. 17–24.
 - [29] Wasmer, K., Nikbin, K. M., and Webster, G. A., “Creep Crack Initiation and Growth in Thick Section Steel Pipes under Internal Pressure,” *Int. J. Pressure Vessels Piping*, 80(7-8), 489–498 (2003).