CRACK GROWTH IN THE PRESENCE OF LIMITED CREEP DEFORMATION

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Abstract

Creep crack growth tests have been conducted on a plain carbon manganese steel, aluminium alloy 2519 and titanium alloy 6242 at 360, 135 and 500°C, respectively, at conditions where only limited creep deformation was observed. The results have been analysed using ASTM Standard E1457-92 which was developed for describing creep crack growth in the presence of extensive creep. It has been found that the creep fracture mechanics parameter C^* defined in E 1457 can also be used to interpret the data

generated in this investigation but that it is necessary for certain restrictions imposed in the Standard to be relaxed to allow the data to be assessed.

Introduction

Failure in components at elevated temperatures can occur by creep crack growth, net section rupture or a combination of both processes. Failure by crack growth is most likely to take place in components which contain a pre-existing defect or sites of stress concentration. When cracking is involved in making ‘fitness-for-purpose’ calculations and estimates of lifetimes, it is necessary to know the criteria governing creep crack growth.

Historically several parameters have been employed to characterise creep crack growth rate [1]. These include stress intensity factor K [2-5], the creep fracture mechanics parameter C^* (and the $C(t)$, C_t , and Q^* variants of this parameter) [6-11], the reference stress σ_{ref} acting on the remaining ligament of a cracked structure [12-13] and a local crack tip opening displacement rate $\dot{\delta}_5$ [14-15]. Typically when these parameters have been applied to describe creep crack growth data on particular materials, cracking rate $\dot{a}$ has been described by relationships of the form

$$\dot{a} = AK^m \quad (1)$$

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

$$\dot{\alpha} = H \sigma_{ref}^p \quad (3)$$

where A , D_o , H , m , ϕ and p are material constants which may be temperature and stress state dependent. Normally in these expressions it is found that $m \approx p \approx n$, the stress sensitivity of creep in the Norton creep law, and ϕ is a fraction close to unity. In general, descriptions in terms of K are restricted to extremely brittle circumstances where an elastic stress distribution is preserved at a crack tip, correlations using σ_{ref} are appropriate to very ductile situations where failure is essentially by net section rupture of the uncracked ligament and C^* has the widest range of applicability.

An American Society for Testing and Materials (ASTM) procedure E1457-92 [16] has been produced for measuring the creep crack growth characteristics of materials. It is relevant to situations involving extensive creep where a steady state creep stress distribution has been established ahead of a crack [1,6-8]. Certain restrictions are imposed to determine when this condition has been reached. This depends upon the relative amounts of elastic, plastic and creep deformation incurred at the crack tip. For a material which undergoes secondary creep according to the law,

$$\frac{\dot{\alpha}}{\dot{\alpha}_0} = \left(\frac{\sigma}{\sigma_0} \right)^n \quad (4)$$

where $\dot{\alpha}_0$, σ_0 and n are material constants, it has been demonstrated [9,17] that a steady state creep stress distribution is achieved after a time t_T given by

$$t_T = \frac{K^2 \dot{Y}}{(n+1)EC^*} \quad (5)$$

where E is the elastic modulus. In E1457-92 data collected at times $t < t_T$ are regarded as invalid. Since K and C^* may vary with crack length and time, the procedure specifies that t_T should be evaluated at all times and its maximum value chosen in order to be conservative, although it may be argued that a steady state creep stress distribution is achieved at a crack tip at an earlier time when t first reaches t_T so that more of the data can be considered as being valid.

Further conditions are imposed in E1457-92 for the valid application of C^* . The procedure describes the test method to be carried out on compact tension specimens containing a prior fatigue pre-crack. Up to 25% deep side grooves (12.5% each side) are permitted to promote flat - straight-fronted cracks. It is required to monitor crack growth a and load point displacement Δ throughout a test and to regard the first 0.5 mm of crack extension and data which do not satisfy the inequality $\dot{\Delta}_c / \dot{\Delta}_T > 0.8$ (where $\dot{\Delta}_c$ is creep displacement rate and $\dot{\Delta}_T$ is total displacement rate) as being invalid although all the data can be reported. All these restrictions are not of serious consequence in the presence of extensive creep. In other circumstances they may never be satisfied or may only be met late in the life of a test.

This investigation was initiated to determine whether some of the restrictions in ASTM E1457-92 can be relaxed, or modified, to enable it to be applied to situations involving only limited creep deformation. The study has been carried out under the auspices of VAMAS (Versailles Agreement on Advanced Materials and Standards) project TWA 19 in association with committee E08 of ASTM.

Experiments

Three materials have been examined, a plain carbon-manganese steel, titanium alloy 6242 and aluminium alloy 2159, with different creep characteristics. The steel was investigated after annealing at 650°C for 3 hours. The titanium alloy was produced with a fully alpha-beta lamella microstructure and the aluminium alloy was obtained in the peak aged T8 temper condition. A series of ‘Round Robin’ experiments was conducted on each material. All the materials were tested under conditions where only limited creep deformation was observed.

Compact tension specimens were manufactured from each batch of material to the dimensions shown in Table 1. Several widths W and gross thicknesses B were employed. All the specimens had 10% deep side grooves inserted into them on each side to give the net thicknesses B_n listed. The titanium and aluminium alloy specimens and two of the C-Mn steel specimens were provided with a pre-fatigued starter crack prior to the introduction of the side-grooves. For the remainder of the steel specimens a fine flat

electro-discharge machined (EDM) notch with a tip radius of 0.05mm was used as a starter crack.

In all cases experiments were carried out at constant load according to the recommendations of E1457-92. The titanium alloy was tested at 500°C, the steel at 360°C and the aluminium alloy at 135°C. The relevant creep ductilities ε_f and creep parameters in the Norton creep law (equation 4) at these temperatures are listed in Table 2 for each material. The loading conditions were chosen to give failure times in the range of approximately 150 to 1000 hours. For all the tests, load point displacement was monitored continuously with the aid of an extensometer. A DC electrical potential method was used to measure crack growth in the titanium and aluminium alloy specimens and either an AC or a DC system was employed for the steel. With these techniques, it is estimated that crack extension could be recorded with an accuracy of $\pm 0.1\text{mm}$ using a linear calibration of voltage change taken between optical estimates of the initial a_o and final crack lengths. It is believed that this procedure is more reliable than the formula given in E1457-92 for the test conditions used.

Examples of the crack extension recorded against normalised time t/t_f (where t_f is failure time) for each material are shown in Fig 1. For each material, little crack growth is experienced for the first approximately one third of life. Also a crack extension of 0.5mm is not observed until 60% of the life has been consumed for the titanium alloy and about 80% of life for the steel and aluminium alloy. Similar trends were noticed in all

the tests. This implies that most of the data collected cannot be regarded as satisfying the requirements of E1457-92.

Examples of the deflection time curves obtained for each material are presented in Figs 2-4. Also included in these figures is the elastic component which was calculated according to the procedure given in E1457. It is evident that considerable plastic deformation was experienced on loading for the C-Mn steel whereas the aluminium and titanium alloys exhibited only elastic deformation on loading. In all cases it is seen that the creep component of the displacement is always less than the elastic component throughout an entire test indicating that cracking has taken place in the presence of limited creep deformation.

Analysis

Because of the limited creep deformation observed, the creep crack growth rates recorded in all the tests have been plotted against stress intensity factor in Figs 5-7. In all cases considerable scatter is obtained suggesting that K is not a suitable parameter for correlating the creep crack growth properties of the materials under the conditions examined.

The ratio of the creep to total displacement rates $\dot{X}_c / \dot{X}_T$ determined throughout the tests is shown in Figs 8-10 for each material. Also included in these figures is the transition time t_T , the time to reach 0.2mm crack extension $t_{0.2}$, the time to reach 0.5mm of crack growth $t_{0.5}$ and the region of validity specified in E1457 (shown hatched) for correlation

of the data in terms of C^* . It is apparent from the restrictions imposed in E1457, that most of the results collected should be regarded as unusable. This is because all the conditions are not satisfied until late in the life of a test.

Additional data can be regarded as acceptable if the restrictions imposed in E1457 are relaxed. The shaded areas in Figs 8-10 show the extra data that can be included if crack growth beyond 0.2mm crack extension and displacement rate ratios $\dot{\Delta}_c / \dot{\Delta}_T > 0.5$ are allowed. For the steel (Fig 8) this means that results collected during about the last half of a test can be analysed. Similarly, for the aluminium (Fig 9) and titanium (Fig 10) alloys data obtained during approximately the last 40% and 70% of life, respectively, could be processed. Creep crack growth data which satisfy these more relaxed criteria are presented in Figs 11-13 plotted against C^* . It is apparent that less scatter is obtained than when K is used (Figs 5-7). There is no trend with specimen size or initial loading conditions. There was also no influence for the C-Mn steel of whether crack extension was measured by AC or DC methods and whether a starter crack was introduced by EDM or pre-fatigue. The largest spread in results is demonstrated by the steel which exhibited significant plastic deformation on loading. However, this spread is consistent with the scatter commonly observed when extensive creep deformation accompanies cracking [1,6-8].

Discussion

Immediately after loading an elastic, or elastic-plastic, stress distribution is generated ahead of a crack tip prior to the onset of creep. The restrictions imposed in E1457 are to ensure that a steady state creep stress distribution has been produced ahead of the crack for the data to be analysed using the creep fracture mechanics parameter C^* . This is achieved at time $t > t_T$. For all the materials examined this condition is reached early in the life of a test (typically after about $0.1 t_f$, Figs 8-10). It is not surprising therefore that correlations of cracking rate in terms of K were not obtained in Figs 5-7.

To obtain a unique correlation of creep crack growth rate with C^* , it is necessary to achieve a steady state distribution of creep damage ahead of a crack tip as well as a steady state creep stress distribution [1,8]. The creep damage gradually builds up from the beginning of a test and is the cause of the initial period of very little crack extension shown in Fig 1. It is sometimes referred to as an incubation period or a ‘tail’ [1,8,18]. It gives rise to a reduced crack growth rate at low C^* early in a test, which is less than that expected after a steady state creep damage distribution has been attained at a crack tip. An illustration of this feature is shown in Fig 12 for the aluminium alloy by the data which lie below the scatter band. This ‘tail’ can be avoided by excluding data prior to the onset of a steady state of damage being reached. In E1457 it is implied that this is achieved after a crack extension of 0.5mm. In this investigation, in most cases it would appear that it is attained after a crack extension of 0.2mm.

The condition specified in E1457 that $\dot{X}_c / \dot{X}_T$ should be greater than 0.8 is included to ensure that creep displacement rate dominates when evaluating C^* from experimental

measurements. It is apparent that relaxation of $\dot{\Delta}_c / \dot{\Delta}_T$ to greater than 0.5 does not cause an increase in scatter of the data over that normally encountered for situations involving extensive creep deformation.

Conclusions

Experimental creep crack growth data have been obtained on a plain carbon manganese steel at 360°C, aluminium alloy 2519 at 135°C and titanium alloy 6242 at 500°C at conditions where only limited creep deformation was observed. The results have been analysed using ASTM standard E1457-92 which was developed for situations involving extensive creep. The Standard specifies that creep crack growth data can only be correlated against the creep fracture mechanics parameter C^* after a steady state creep stress distribution has been reached at a crack tip, 0.5mm of crack extension has taken place and the creep displacement rate $\dot{\Delta}_c$ to total displacement rate $\dot{\Delta}_T$ ratio $\dot{\Delta}_c / \dot{\Delta}_T > 0.8$. In this investigation these latter two conditions could only be met late in the life of a test. However, it has been found that if they are relaxed to a crack extension of 0.2mm and a ratio $\dot{\Delta}_c / \dot{\Delta}_T > 0.5$, correlations of cracking rate in terms of C^* can be achieved which show similar amounts of scatter to those experienced for situations involving extensive creep.

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Table 1: Compact tension specimen dimensions

<i>Material</i>	<i>W (mm)</i>	<i>B (mm)</i>	<i>B_n(mm)</i>
C-Mn	25.3	12.6	10.1
Al -2519	50.8,	22.1, 6.35,	17.7 5.1
Ti-6242	50.8, 38.1	6.35	5

Table 2: Creep properties of materials

<i>Material</i>	<i>Temp.(°C)</i>	ϵ_f %	<i>n</i>	σ_d (MPa)
C-Mn	360	15	11	876
Al -2519	135	5	30	369
Ti-6242	500	15	5	2936

Figure Captions

Figure 1: Examples of crack extension versus normalised failure time for each material with initial crack length a_0 in mm, initial K_0 in $\text{MPa}\sqrt{\text{m}}$ and failure life t_f in hours

Figure 2: Components of the load-line deflection for C-Mn steel specimen at an initial stress intensity factor of $53.6 \text{ MPa}\sqrt{\text{m}}$

Figure 3: Components of the load-line deflection for an aluminium alloy specimen at an initial K of $16.6 \text{ MPa}\sqrt{\text{m}}$

Figure 4: Components of the load-line deflection for a titanium alloy specimen at an initial K of $45.73 \text{ MPa}\sqrt{\text{m}}$

Figure 5: Correlation of creep crack growth rate versus stress intensity factor for C-Mn steel at 360°C

Figure 6: Correlation of creep crack growth rate versus stress intensity factor for aluminium alloy 2519 at 135°C

Figure 7: Correlation of creep crack growth rate versus stress intensity factor for titanium alloy 6242 at 500°C

Figure 8: Ratio of creep load-line deflection rate to total load-line deflection rate versus normalised time for C-Mn steel at 360°C

Figure 9: Ratio of creep load-line deflection rate to total load-line deflection rate versus normalised time for aluminium alloy 2519 at 135°C

Figure 10: Ratio of creep load-line deflection rate to total load-line deflection rate versus normalised time for titanium alloy 6242 at 500°C

Figure 11: Creep crack growth rate versus C^* for C-Mn steel at 360°C

Figure 12: Creep crack growth rate versus C^* for aluminium alloy 2519 at 135°C

Figure 13: Creep crack growth rate versus C^* for titanium alloy 6242 at 500°C

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Figure 8: Ratio of creep load-line deflection rate to total load-line deflection rate versus normalised time for C-Mn steel at 360°C

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Figure 10: Ratio of creep load-line deflection rate to total load-line deflection rate versus normalised time for titanium alloy 6242 at 500°C

Figure 11: Creep crack growth rate versus C^* for C-Mn steel at 360 °C

Figure 12: Creep crack growth rate versus C^* for aluminium alloy 2519 at 135 °C

Figure 13: Creep crack growth rate versus C^* for titanium alloy 6242 at 500 °C